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REFERENCE

Lane, B. H., 1935, Suggestions to authors of papers submitted for publication by the United States Geological Survey: U. S. Geol. Survey, Washington, D. C. (For sale by Superintendent of Documents, Washington, D. C. 35c.)

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ORGANIC REEFS AND BANKS AND ASSOCIATED DETRITAL SEDIMENTS*

F. STEARNS MacNEIL

ABSTRACT. Definitions of reef are reviewed, and a revised definition is proposed. A plea is made for the retention of reef as a physiographic term to be consistent with the classification of reefs as fringing reefs, barrier reefs, and atolls. Webster's International Dictionary defines a reef as a rocky elevation or knoll (a shoal if not rocky) lying between low water level and a depth of 6 fathoms, and a bank as an elevation, rocky or not, covered by more than 6 fathoms of water. A growth lattice is here defined as a rigid framework formed of the skeletons of usually calcareous sessile organisms—corals, oysters, bryozoans, other animals or algae. The structure is often imbricating and interstitial cavities are usually present. Bioherm is preferred for growth lattices whose vertical dimension exceeds the thickness of sediments deposited contemporaneously. Reef rock is acceptable for the rock of all facies of organic reefs or banks. If composed mainly of a growth lattice, it might be termed biohermal reef rock. If composed of reef detritus or the skeletons of solitary organisms, it might be termed detrital reef rock. Most modern reefs consist of both biohermal and detrital facies. The aggregate of all types of reef rock is the reef rock complex.

Detrital reef rock does not always contain recognizable corals or other reef-forming organisms. Mainly foraminiferal limestones and fine-grained lime sands may be lagoon deposits from which the retaining biohermal facies has been eroded.

Reefs supply greater quantities of detritus than banks. Live reefs can supply limitless quantities of detritus. The volume of detritus obtainable from a dead reef is limited to the volume lying within the zone of effective erosion. Raised reefs are removed mainly by solution and furnish little or no detritus.

The four main categories of reefs are maintained. They are: 1) fringing reefs (reefs growing along the edge of land), 2) table reefs (isolated flat-topped reefs without lagoons), 3) barrier reefs (reefs sparated from land by a lagoon), and 4) atolls (annular reefs enclosing lagoons).

Banks are typically round or irregular. Elongate banks paralleling land are termed "barrier banks." Annular banks are termed "annular banks" or "atoll-shaped banks."

Small annular reefs forming part of a barrier or atoll are called faros. Reefs made up of faros are called faro-type barriers or faro-type atolls.

Intermediate and borderline reef types are discussed in the text.

REEF

The term "reef," like so many terms common to more than one field of endeavor, has become an inexact word with a variety of meanings. Webster's International Dictionary defines reef (under "shoal") as "a rocky elevation or knoll on which there is a depth of water of 6 fathoms or less at low water." To the navigator, a reef is a rocky knoll or rock ridge that rises to the surface, or close enough to the surface, to endanger ships. The organic reefs of the tropics are called coral reefs. Students of living reefs give the word a similar connotation. The classification of reefs as fringing reefs, barrier reefs, and atolls implies that they separate land from water, that they are separated from land by water, or that they separate two bodies of water and therefore are surface or near-surface features.

* Publication authorized by the Director, U. S. Geological Survey.

Cumings (1932, p. 333) says:

"There is no intimation, nor should there be, in the commonly accepted meaning of the word reef, that the structure is organic or otherwise; but there is the clearest possible specification that it is a structure rising close to the surface of the water, from presumably navigable depth, and having a ridgelike or riblike form."

Geologists, on the other hand, most of whom have had no experience with recent reefs, have come to interpret and define reefs solely on the basis of organic features that they have observed in rocks. In some definitions reef is restricted to a growth lattice and excludes the detrital materials derived from it. With few exceptions, geologists ignore the condition of proximity to the surface of the water in their definitions—even though this is part of the explicit meaning of the word. The concept most geologists have of a reef agrees more closely with the definition of a bioherm, a term proposed by Cumings for moundlike organic growths in rocks of different lithology and therefore by inference a structure whose vertical dimension exceeds the thickness of sediments deposited contemporaneously. Opinion may differ as to whether Cumings intended the term bioherm for growth lattices only. The writer holds that greater uniformity in terminology can be achieved if bioherm is used in this way and the dictionary definition of reef is maintained.

ORGANIC REEFS

During the past decade research on the multitudinous problems of coral reefs has been much accelerated, partly because of military necessity, and partly because of the search for bioherms in rocks of all ages as possible oil reservoirs. As a result a number of comprehensive papers and symposiums have been published. Many of these have contained definitions. Some contain statements with which other geologists and students of living reefs take issue. Probably the most debatable points involve: 1) whether reefs should be defined on the basis of form or content, 2) whether organic detritus should be included as part of a reef, and 3) the relative abundance of organisms in situ and organic detritus. It seems clear, however, that a definition acceptable to geologists must not only take into consideration the characteristics of existing organic reefs and banks but also must cover the form and content of fossil bioherms, their associated detrital facies, and their relationship to the sediments enclosing them.

Wilson (1950, p. 181) gives the following definition of an organic reef:

"A reef is a sedimentary rock aggregate, large or small, composed of the remains of colonial-type organisms that lived near or below the surface of water bodies, mainly marine, and developed relatively large vertical dimensions as compared with the proportions of adjacent sedimentary rocks. The organisms, generally corals and algae and less commonly crinoids and bryozoans, creating the essential features of a reef, lived their mature lives on it and their hard parts remain in place there after death. Reefs tend to develop as mounds or ridges but also grow in irregular, asymmetrical forms. In all, however, a rigid framework enables a reef margin to grow upward and outward at much steeper angles (even vertical) than is the case with sedimentary clastic rocks. Reefs are commonly characterized by lack of well developed stratification. Differential settling in rocks adjacent to them usually causes draping of strata over reefs. The extra weight of reefs may cause downward bending of strata under them. Clastic materials or chemically precipitated sediments may be substantial constituents of reefs but are not distinctive parts of them."

In the same symposium Twenhofel (1950, p. 183) described an organic reef as follows:

"The writer's understanding of an organic reef or bioherm is that it is an aggregate of organic materials of significant dimensions built in part by colonial organisms, mainly, but not necessarily marine, that lived near, but below, the surface of the water (they may have some exposure at low tide) and constructed exoskeletal matter that became more or less adherent to previously formed similar matter. Nooks and depressions between the structures made by the colonial organisms, which may have as much space as, or greater than, the structures made by them, formed excellent dwelling places for noncolonial organisms which sought these places for protection or for food. Organic reefs develop substantially large vertical dimensions as compared with the dimensions of adjacent contemporaneous deposits. Organisms responsible for the somewhat rigid framework of a reef are permanent dwellers on it and their exoskeletons or secretions remain to make a part of it after their deaths. As the structure developed by the building of the forming organisms has considerable rigidity, it does not change volume under the weight of any overburden placed upon it. In a sense, the complete structure is reinforced by the overlapping colonial growths and this reinforcement enables the accumulation to grow upward at much steeper angles than is possible for most sedimentary materials and certainly for all clastic materials. Inclinations beyond the vertical are possible. Contact of a reef with marginal sediments is irregular and at angles that are not possible with ordinary sediments. This contact may be horizontal both above and below, and thence it may range to vertical."

Cumings (1930, p. 207) defines a bioherm as follows:

"A bioherm is defined as consisting of any dome-like, mound-like, or otherwise circumscribed mass, built exclusively or mainly by sedentary organisms such as corals, stromatoporoids, algae, brachiopods, mollusca, crinoids, etc, and enclosed in normal rock of different lithologic character."

The lack of distinction between reef and bioherm by some geologists, between reef and bank by others, as well as the emphasis placed on the nature of enclosing sediments is apparent in the above descriptions. These lengthy and carefully worded definitions of reef and bioherm, though probably descriptive of the type of structure that might grow as an organic bank in a shallow epicontinental sea, or on a continental shelf, would not appeal to a present-day student of oceanic atolls, except possibly as the description of a coral knoll growing in a lagoon. It is now known that, contrary to long-standing belief, the growth lattice of living organisms may be a subordinate constituent of atolls and other large reefs, and that detrital material derived by the forced movement and breaking up of algae and corals and the frequently more abundant skeletons of Foraminifera are a major if not a predominant part of modern reefs.

Just what part of an atoll, if it were examined in the geologic column, might be identified as a reef is a subject for thoughtful speculation. If the term were restricted to the biohermal portion, only the growing edge, and knolls in the lagoon might be so identified. Detrital sediments intertonguing with the zone of organic growth, such as are found on an existing reef flat might be identified as back-reef detritus,[1] just as the steeply dipping talus deposits along the outer submarine slope probably would be classified as fore-reef detritus.[1] Yet in the present geologic phase, which is believed to have followed closely a drop of sea level and resulted in the planation of a surface across structures of organic growth and detrital sediments alike, we have a feature that has never been called anything but a reef. To restrict the term reef to the growing portion would be to call the seaward margin a reef whereas the reef flat is not a reef!

[1] See page 390.

Ladd (1950, p. 204) pointed out this discrepancy in definition.

"In recent years—having examined some of the larger recent reefs and having done some diving and dredging in their lagoons and on their outer slopes—the writer has come to realize that though the rigid framework is a very essential part of a reef—like the walls and rim of a pail that holds water—it may quantitatively be very unimportant and only in rare elevated reefs is it preserved and satisfactorily exposed."

Fairbridge (1950, p. 330) found the same to be true of the reefs of Australia.

"In both living and ancient reefs the proportion of actual colonial corals grown *in situ* is extremely small in relation to the enormous quantities of 'coralline' sedimentary debris."

Eleswhere Ladd (1950, p. 203) states:

"Living reef-building organisms are concentrated along the seaward margin where they form a rigid, wave-resisting framework. Most reef surfaces show a distinct zonation parallel with the reef front. Sedimentary materials increase landward or lagoonward and where lagoons are present the sediments may form the major part of the reef. Extensive sedimentary deposits likewise accumulate off the seaward side of the reef."

Twenhofel recognized the presence of broken-up organic material in fossil reefs but did not relate it to the physical rigors of their environment. He says (1950, p. 183):

"After the deaths of the reef-builders, their constructions may be riddled by boring organisms in their search for food or to construct cavities in which to live. In this way the framework of the structure may be greatly impaired and reduced in part to calcareous sand and mud, and this destruction may be so complete that the resulting materials may show little evidence of once having been a rigid framework."

The statement in Wilson's definition that "reefs are commonly characterized by lack of well developed stratification" would need some qualification to satisfy students of existing atolls. There are few thinly bedded deposits, but well-developed strata from 6 inches to 2 feet in thickness are common. As pointed out by Ladd, only the seaward margin of the reef is a wave-resistant framework of reef-building organisms. Battering of the growing edge by waves produces detritus of all sizes that is carried lagoonward to form stratified deposits. Typhoons cast great quantities of coarse rubble onto the reef flat and lagoon bench where they form definite strata, those on the lagoon bench often alternating with layers of coral in growth positions. Although some parts of reef flats are erosional features and support no important growth of organisms, rubble deposits thrown onto them may, during periods of subsidence or of positive eustatic shift, accumulate vertically to form a sequence of coarse-textured strata.

In the northern Marshalls there are many remnants of elevated reef flats, most of which form the cores of vegetation-covered islands. Strata of different texture, hardness, and weathering properties were observed in many of these raised reef platforms. All were composed of detrital materials. In many places the present reef flat is trenched by trans-reef spillways that may be cut back from the lagoonward edge to the center of the reef flat or beyond. The rock exposed along the sides of the spillways is stratified and consists of alternating beds of coarser and finer detritus. Difference in hardness is indicated by the recession and projection of alternate layers. The part of the seaward marginal zone available to direct examination, however, seems to be entirely the result of organic growth, and it is doubtful if detritus can be added to it except to fill an occasional nook or cranny.

In view of the inconsistencies pointed out, and at the risk of further beclouding an already ambiguous term, the writer makes one more attempt to define an organic reef:

An organic reef is a rigid structure—composed of the calcareous skeletons of: 1) colonial and commensal animals or plants, whether algae, corals, stromatoporoids, mollusks, bryozoa, or others, interlocked or cemented together by growth; 2) all detrital materials derived from the breaking up of the colonial organisms (which might be unconsolidated when deposited but which may become indurated later); and 3) the remains of organisms which normally live in, on, or near the organic lattice, such as foraminifers, crabs, echinoids, and other forms, which are added either to it or to the detrital deposits—which grows independently of and builds up at a rate greater than all surrounding types of sediments (except where becoming part of the reef body), and maintains its upper growing or depositional surface at or near the level of the sea (some parts of which may be exposed at low tide). During periods of emergence the upper surface of a reef may become a surface of planation due to solution and erosion. A surface of planation may result without emergence where storm-cast detritus has become cemented to the reef and has been eroded subsequently. An organic reef may thus consist of a bioherm alone, or of a bioherm and detrital materials derived from it and other organic remains normally brought to it, which together, by growth and accumulation, and without other outside assistance, maintain a prominence close to sea level. A living reef may, therefore, extend upwards far above the level of contemporaneous surrounding sediments, and a reef in the geologic column may have great vertical dimensions compared with surrounding sediments and be separated from them by nearly vertical or greater than vertical boundaries. Detrital materials derived from the biotic community, which do not contribute to the building of the near sea level component, such as those settling in the lagoon or on the steep submarine slope, though not reef in the navigator's sense, are nevertheless an important part of the reef structure, and in a buried reef would be more related in composition, texture, porosity, and genesis to the reef than to any surrounding rock.

A certain amount of ambiguity may be expected if the term "reef" is used for reeflike structures in the geological column. There is no objection to using the term "reef" for both reefs and banks where the distinction is not apparent. However, indiscriminate use of the terms "reef" and "bioherm" should be avoided.

It might be pointed out that the definitions adopted here do not agree entirely with the views of some other recent contributions. Link (1950, p. 263) says:

> "A "bioherm" is an accumulation of the secreted hard parts of sessile types of primitive invertebrates and plants such as corals, bryozoans, crinoids, sponges, algae, *et cetera*, which accumulation is greater than the surrounding contemporaneously deposited sediments, thus giving rise to mounds, ridges, or reefs. Therefore, 'coral reefs' and 'bioherms' are, in a sense, one and the same. According to what organisms predominated to cause it, such an accumulation is termed a 'coral-reef' or 'coral bioherm;' a 'bryozoan reef' or 'bryozoan bioherm;' an 'algae reef' or 'algae bioherm,' *et cetera*. When in doubt one should refer to them as 'bioherms' or 'reefs' without commitment as to composition."

Link's definition is a poor one in the writer's opinion. It takes from reef its most explicit meaning, a rocky elevation lying at or near the surface of the water, and makes it a synonym of a term designed for a biological structure which might lie anywhere. Deeply submerged coral growths more properly known as banks would be reefs according to Link. Organic banks may be bioherms, but they are not reefs. Link loses sight of two other facts: that a reef need not even be organic, and that the biohermal facies need not constitute all of an organic reef.

Lowenstam (1950, p. 430) preferred to think of reefs in terms of potential rather than present-day appearance. He says:

> "Reefs are defined in terms of fundamental biologic potentials of the organisms responsible for them rather than in terms of the present day appearance of the structures. These potentials are the ability to erect rigid topographic structures by frame-building, sediment retention and binding, and to create a wave-resistant structure."

Cloud (1952, p. 2125) concurred in Lowenstam's definition and went further to suggest that bioherm might be retained for ancient reeflike masses of uncertain potential or of doubtfully wave-resistant nature.

It seems to the present writer that bioherm might have more use if used for growth lattices, ancient or modern. Potential would appear to be more a property of a bioherm than a reef, for a reef by virtue of being a sea level or near sea level feature is a wave-resistant structure.

REEF ROCK AND REEF ROCK COMPLEX

Reef rock is recommended as a name for the rock, biohermal or detrital, of reefs or banks. The term "reef rock" then comes to apply to rock having a common genesis, different from that of all alien surrounding rock. Reef rock might be subdivided into biohermal reef rock, or rock composed of the growth lattice of organisms, and detrital reef rock, or rock composed of detritus derived from the bioherm. Any reef rock contains a component of unattached organisms that lived on or in the bioherm or detritus. The presence of mostly biohermal rock in such structures might indicate that they were organic banks, whereas the presence of large amounts of detrital rock associated with the biohermal rock should be indicative of reefs.

It seems difficult to exclude lagoon deposits and outer slope talus from the category of reef rock inasmuch as they are derived largely from the fragmentation of the reef. The terms "back-reef clastics" and "fore-reef clastics"[2] have been used for detrital reef rock lagoonward and seaward from the biohermal zone, but not, apparently, strictly for lagoon filling and outer slope detritus. Most geologists are apparently unaware that the greater part of some existing reef flats is composed of detrital reef rock.

Fringing reefs and table reefs may have zones of fore-reef detritus extending downward along their outer slopes. Barrier reefs and atolls may have fore-reef detritus extending seaward and back-reef detritus extending lagoonward. Detrital facies of the reef may intertongue with biohermal facies nearest the biohermal zone. The outward extension of the fore-reef detritus usually intertongues with alien sediments.

[2] Because of the inadvisability of using adjectives as nouns, *fore-reef detritus* and *back-reef detritus* are preferable.

In a recent paper, Henson (1950, p. 215) uses the term "reef-complex" for the aggregate of reef limestones and the calcareous rocks genetically (?) associated with them. Reef complex has been used as an ecologic term, and it is suggested that reef rock complex might be a more appropriate lithologic term. With the possible exception of Henson's fore-reef basin and open basin categories, which seem to strain the concept of reef in its broadest sense, reef rock complex might be a good generic term for all types of rock that either form or are derived directly from organic reefs.

RECOGNIZABLE REEF-FORMING ORGANISMS IN REEF ROCK

Ladd and Hoffmeister (1936) recalled statements by earlier workers that "raised atolls" are not composed of coralliferous limestone and could not, therefore, have been atolls. They pointed out, furthermore, that some atoll-shaped islands studied by them in Fiji appeared "to be composed entirely of bedded Tertiary foraminiferal limestone—limestone that never had any connection with a coral reef." The conviction that "many elevated coral reefs have a foundation of noncoralliferous limestones" led Ladd and Hoffmeister to exclude the noncoralliferous limestones from the category of reef limestones, and to argue further that it was difficult to account for the growth of atolls by subsidence if the foundations of atolls were noncoralliferous limestone, often greatly older than the reefs they supported. This led Hoffmeister and Ladd (1944) to include platforms of depositional limestone as possible foundations for reefs in the antecedent-platform theory.

As a result of his later work, however, Ladd became one of the first to realize that reef rock does not always contain recognizable corals or algae. Ladd and Tracey (1949) came to the conclusion that even some noncoralliferous limestones might be of reef origin and that they could have been bounded on the outer side by biohermal structures that would naturally be the first part to be eroded away on exposure. They state:

> "Since 1945 Hoffmeister and Ladd have studied both existing and elevated reefs in various parts of Micronesia and now feel that they were too restrictive in their identifications of 'reef limestone.' They failed to recognize that 'reef structure' (imbricating colonies of flat corals in positions of growth such as characterized the marginal zones of existing reefs) forms a very small percentage of the entire reef. It is an important part, to be sure—as important as the sides of a pail that holds water—but it may make up only 5 to 10 percent of the reef mass, and, furthermore, may be the first part to be destroyed when the reef is elevated and eroded. By thus recognizing the quantitative unimportance of reef structure, the occurrence of scattered reef corals that are *not* in position of growth assumes greater significance. Such occurrences may indeed suggest a talus slope or deposition on a submarine bank, only parts of which projected into the zone of reef growth, but it is perhaps more likely that such scattered corals were deposited on the side reef flat behind the marginal zone or in the shallow waters of a lagoon.
>
> A second factor overlooked by Ladd and Hoffmeister was the significance of texture in sediments. Fine sediments do not accumulate on unprotected banks, and, therefore, the occurrence of thick sections of such materials is evidence of the existence of a protecting rim at the time of accumulation, even though such a rim may no longer exist."

In view of these discoveries it seems difficult to exclude any raised insular limestone in the tropics from the category of reef rock. Such limestones were deposited on insular shelves, and even though such parts that remain may contain few or no corals, many or most of them may be lagoonal deposits

consisting largely of reef debris or Foraminifera that lived on or in a reef. The burden of proof would rest with the one seeking to show that no bioherm ever bounded them.

DETRITAL SEDIMENTS ON REEFS AND BANKS

The condition under which detrital sediments are formed on existing reefs and banks is important to the identification and interpretation of reeflike structures in the geologic column. It is particularly important when evidence of transgression or regression is sought. The following conditions were found to exist in the Marshall Islands.

The greatest amount of detritus on existing reefs comes from normal wave fragmentation of the growing edge. An almost equally abundant source is the Foraminifera which live on the reef flat. Locally, large quantities of detritus are cast onto the reef flat from the submarine slope by storms.

Storm-cast debris consists largely of coral fragments and shows its derivation from the shallower part of the submarine slope where corals abound. Sediments along the lagoon margin of windward reefs consist mostly of fragments of coralline algae and Foraminifera with subsidiary amounts of coral. The bulk of this material comes from the algal ridge at the seaward margin and from the reef flat and is carried lagoonward by normal trans-reef currents. Dredging in the deeper parts of the lagoon at Bikini showed the bottom sediments to consist mainly of *Halimeda* segments, derived, presumably, directly from the extensive patches of *Halimeda* covering the lagoon floor.

Very little work has been done to date on the detrital facies of organic banks. Probably a close analogy could be presumed from a coral knoll studied in the lagoon at Bikini. The top of the knoll lies at a depth of about 6 fathoms. Detritus obtained from the knoll is stated (Ladd, Tracy, Wells, and Emery, 1950, p. 422) to consist over half of material coarser than 2 millimeters of which 80 percent or more is *Halimeda* segments. Coral fragments, mollusk shells, and discoid Foraminifera form a small proportion of the material.

Solution, which leaves no detritus, is much more effective than wave fragmentation in removing elevations on existing reefs. At a number of places in the Marshalls large, jagged pinnacles composed of the algae *Porolithon* in growth position are present immediately behind the present algal (Porolithon) ridge. These pinnacles presumably are remnants of an algal ridge that formed at the time of a higher sea level. At present these pinnacles are weathering in a manner typical of limestones with smooth solution pits and sharp points and are producing no detrital materials whatsoever.

It might be concluded from these facts that: 1) a live surface reef can supply a limitless amount of detrital material by virtue of its continuous growth, 2) the volume of detritus obtainable from a dead reef would be limited both by the volume of the reef lying within the zone of erosion and by the greater effectiveness of solution which leaves no detritus, 3) a large part of the detritus on a reef comes from normal wave fragmentation of its growing edge, 4) the detritus accumulating on a bank is limited largely to the accumulation of skeletons of solitary organisms such as mollusks and

Foraminifera and disassociated segments of such forms as *Halimeda*, and 5) mechanical fragmentation on banks is a minor factor.

These principles if applied to organic structures in the geologic column might carry the following implications:

1) Large amounts of detritus in association with a bioherm might be indicative of reefs, whereas small amounts might be indicative of banks.

2) Large amounts of fragmental rigid attached organisms, especially near the crest of the organic structure, might be indicative of reefs, whereas detritus near the crest consisting mostly of solitary organisms and disassociated segmented organisms might be indicative of banks.

3) A high percentage of Foraminifera and disassociated segmented organisms in back-reef detritus might be nonindicative of whether the sediments were deposited in lagoons adjacent to reefs or depressions adjacent to banks; a high percentage of fragmental rigid attached organisms should be strong evidence that the sediments area was bounded by reefs.

4) If evidence indicates a transgressing sea, a large amount of reef detritus probably indicates the change of sea level took place slowly. Rapid transgression might convert reefs to banks and lessen the amount of detritus produced.

5) If evidence indicates a regressive sea, a large amount of back-reef detritus probably indicates the change of sea level took place slowly. Sudden emergence of the reef would cut off the supply of reef detritus to the back reef area. Slow regression might allow solution to maintain the reef at sea level without noticeable decrease in back-reef detrital deposits. This situation is analogous to the one now existing in which, despite a eustatic fall of several feet, the reefs of the world have been almost completely planed to a new level.

CLASSIFICATION OF ORGANIC REEFS

Most organic reefs are now classified according to four types: 1) fringing reefs, 2) table reefs, 3) barrier reefs, and 4) atolls. In addition there are minor types, mostly incipient off-shore forms, whose small size, irregularity in plan or relief, or depth below the water surface, makes them difficult to classify. Bioherms too far below the surface to be reefs are called organic banks; those enclosing deeper water are in effect barrier banks or atoll-shaped banks. Six fathoms is taken as the depth separating reefs from banks (Webster's International Dictionary). Some barrier banks and atoll-shaped banks actually are drowned barrier reefs and atolls, but such terms as drowned atoll or submerged atoll should be used only in a genetic sense and not to classify them as they now exist. Small annular reefs that are located along barrier banks and atoll-shaped banks or that form disconnected parts of barrier reefs and atolls are called faros.

Minor types of coral growth are designated as follows: 1) coral heads—single colonies with subequal vertical and lateral dimensions (most heads range between 1 inch and 10 feet in diameter), 2) compound coral heads—small masses with subequal vertical and lateral dimensions and consisting of more than one colonial colony of the same or different species, 3) coral knolls—columnar or irregular growths of coral with greater vertical than

lateral dimensions, rising from the floor of a lagoon, occasionally reaching the surface of the water to form a "lagoon table reef." 4) coral patches—submerged growths of coral with large lateral and small vertical dimensions, often covering large areas of the bottom, but rising only a few feet above the bottom. 5) microatolls—massive colonial corals growing peripherally in shallow areas and whose dead upper surface (sometimes made concave by solution) is exposed at low tide. Microatolls often form a pavement of closely spaced stepping stones.

Fringing reefs.—The fringing reef (sometimes called shore reef) is perhaps the simplest of all reefs. It is merely the growth of reef-forming organisms along the edge of land, and no explanation is required for the site on which it grows. Fringing reefs may range from only a few feet in width to over 2 miles, but reefs over a quarter of a mile in width are not common. A low off-shore gradient may be more favorable to the formation of a broad reef than a steep one. The most vigorous fringing reefs are found along the shores of islands. Along continental borders there may be excessive sedimentation or excessive dilution of sea water with fresh water from streams, both detrimental to corals and algae. The outstanding exception is the semi-arid shore of the Red Sea where a nearly unbroken fringing reef extends for over 2700 miles. Fringing reefs may adjoin cliffs, beaches, or swamps. The seaward edge may face the open sea (exposed fringing reefs), or it may border a lagoon enclosed by a barrier reef, or it may have the semiprotection of off-lying land which in turn may have a fringing reef. It is not uncommon for the lagoon separating fringing and barrier reefs to be discontinuous, and where there is no lagoon the entire reef would be classified as a fringing reef.

Table reefs.—The term table reef was proposed by Tayama (1935) as a late addition to the nomenclature of reefs. It was meant to include isolated flat-topped reefs with no lagoon. More recently Fairbridge (1950, p. 345) expressed preference for the term "platform reef," believing it to have priority over table reef, and for small platform reefs he proposed the term "patch reef." Concerning the priority of platform reef and other names applied to reefs of this type Fairbridge (1950) says:

> "Jukes, Dana, Stephenson, Spender, Steers, and others refer to these as 'inner reefs,' meaningless when there is no barrier. Niermayer (1911) named them *plaatrif*, which I translate as 'platform reef.' Molengraaff (1930) translated it as 'shoal reef,' but Teichert (1947) gave 'shelf reef' or 'hummock reef.' Davis (1928) calls them 'bank reefs.' *Plaatrif* considerably antedates Tayama's 'table reef' (1935), recently adopted by Ladd."

Platform reef can certainly be used as a cognate of table reef, designating the very large ones. There is considerable doubt that Fairbridge's translation of plaatriff to mean a reef forming a platform rather than a reef growing on a platform (shelf) is correct. Davis clearly meant bank reef for reefs growing on shallow shelves. Fairbridge restricted the terms platform reef and patch reef to reefs without islands, because he believed those with islands present special problems. There is some ambiguity here between the shape of reefs and the position of reefs. To be consistent with Fairbridge's term "shelf atoll" (p. 396-397), table reefs on continental shelves might be called shelf table reefs or shelf platform reefs. Actually, there is no reason

why a foreign word, plaatriff, or its translation should take priority in English over a word proposed in the English language.

Table reefs may rise from shallow sea floors, continental and insular shelves, lagoons, submerged karst, drowned islands, or from prominences rising from the depths of the ocean, such as submarine folds or submarine volcanic features of any kind. The only requirements necessary are: 1) that there be on the foundation some object hard enough and large enough to enable the first reef-forming organism to attach itself, and 2) that the shelf or promontory be within the phototropic range of the organism. Some table reefs may be elongated and curved, or U-shaped, and approach atolls in shape. It is here proposed that reefs of this type be known as curved table reefs if the foundations on which they rest are of this shape, but that if the foundations are closed figures, even though there are large gaps in the reef, they be known as atolls. The terms "near-atoll" and "semiatoll" have been used for atolls with very large reefless segments.

Small table reefs might be the precursors of several larger types of reefs. Those growing along the edge of a shelf might in time become sufficiently elongate to form a barrier and thus become barrier reefs. Other table reefs close to shore might eventually make contact with the shore and form a fringing reef or coalesce with a fringing reef.

Darwin classified a few table reefs lying as much as 3 miles off shore, and separated from the shore by very shallow lagoons, as fringing reefs. His intent is clear; he wished to distinguish them from barrier reefs, which according to his theory form as the result of the upward growth of the edge of a fringing reef following submergence of the platform, and which should, therefore, be separated from land by a moderately deep lagoon. Even though, according to his theory, such reefs might be incipient barriers, he would still regard them as fringing reefs.

Barrier reefs.—A barrier reef is an elongate reef enclosing a lagoon on one side, the other side of the lagoon being bordered by nonreef-built land, a fringing reef, or a parallel barrier reef (the two forming in this case a double barrier reef behind which is still another lagoon). Annular reefs enclosing lagoons in which there are nonreef-built islands are barrier reefs, but annular reefs enclosing barren lagoons or lagoons containing coral knolls, table reefs, or islands composed of reef detritus only are atolls. Davis (1928, p. 7) used the term "almost-atoll" for reefs whose lagoons are "so little occupied by islands (of alien rock) that their reefs almost become atolls."

Barrier reefs, like table reefs, may grow on a variety of foundations, even mud. Corals attach themselves to hard objects, but it need be nothing more than the shell of a deceased wandering mollusk. A colonial coral may grow on it, other corals and algae attach themselves to the first coral, and a new communal structure is started. Such communities may settle in soft sediments under their own weight, but in time they may become large enough to cover large areas and build up to the surface to form table or barrier reefs, their exact shape depending on external physical conditions. Barrier reefs owing their location and shape to already existing submarine topography

(inherited shape) present special problems related to eustatic shifts of sea level, tectonic movements, subaerial erosion, and other factors and will be discussed in the paper on the origin of atolls.

The Great Barrier Reef of Australia is not a barrier reef in the strict sense, but a complex group of reefs covering an entire continental shelf, in places over 100 miles wide. The true barrier reefs along the outer edge of the Great Barrier Reef rise from about the 100 fathom line and were termed linear reefs by Jukes (1847). More recently Fairbridge (1950, p. 338) called them ribbon reefs. Along other parts of the Great Barrier Reef there are no true barrier reefs, the outermost reefs being large table or platform reefs located several miles back from the 100 fathom line, and similar to the table reefs that lie behind the ribbon reefs elsewhere.

Atolls.—An atoll is an annular reef enclosing a lagoon in which there are no promontories other than reefs and islands composed of reef detritus. Atolls commonly are oval or circular but may be very irregular. The opposite sides may converge to form two or more lagoons. Some atolls are without islands whereas others have islands around the greater part of their reef. Occasional atolls are continuous (complete atolls), but most atoll reefs have gaps or passages that may have considerable width or depth.

The degree of annularity separating a near-atoll from a curved table reef is not rigidly defined. It was proposed in the discussion of table reefs that the distinction be based on the shape of the submarine platform as well as on the completeness of the exposed ring. Greater than semicircular reefs might be called near-atolls if their foundations are closed figures capable of supporting reef across the unfilled gap, whereas if the platforms are curved or U-shaped and the reef covers their top completely they should be called table reefs. A narrow reef growing all around the edge of a U-shaped platform and enclosing a U-shaped lagoon might be either an atoll or a faro, depending on its size and the presence or absence of other faros.

Most students of atolls agree that there is no significant difference in appearance between atolls growing on continental shelves and atolls rising from oceanic ridges and sea mounts. However, the shapes they assume may be due to different factors, those on the continental shelves being fashioned primarily by the force of prevailing wind and waves. These forces also affect oceanic atolls, but some oceanic atolls probably reflect to a large extent the shape of their platforms.

Names have been proposed for the atolls of continental shelves to distinguish them from oceanic atolls. Davis proposed (1928, p. 19) that reefs lying back from the edge of the continental shelves be known as "bank reefs," and that if annular they be known as "bank atolls." Those lying in lagoons behind barrier reefs he called "lagoon atolls" (small annular reefs enclosing little lagoons in the larger lagoon). Fairbridge (1950, p. 341) proposed the term "shelf atoll." He says:

"Davis (1928, p. 19) called the annular reefs which rise from relatively shallow platforms, 'bank atolls.' By 'bank' he clearly meant such structures as continental or insular shelves, and not those features of the shelf such as sand banks, e.g., Dogger Bank in the North Sea. Molengraaff (1930, p. 56) considered these atolls as a variety of shore or fringing reefs, because their foundations do not descend into deep water, and he called

them 'pseudo-atolls.' This term, however, had already been used by Agassiz and others for platform reefs with shingle rims and shallow reef pools. The term is not very satisfactory because it implies something that is not a true form. The present writer prefers the term 'shelf atoll' because it means what it says: an atoll associated with a shelf area."

Fairbridge's distinction between a bank, which is an isolated elevation under the sea, and a true continental shelf, seems appropriate. Conceivably atolls might be located on alien foundations that once formed inorganic banks, but even so they are atolls without qualification.

Atolls at sea level, that is, atolls whose reefs are constructed to or planed to a level within the tidal zone, are atolls in the strict sense of the word. The presence of islands composed entirely of storm-cast, wave-piled, or eolian detritus does not alter the fact that the reefs supporting them are sea level reefs. However, there are many examples in the world of atoll-shaped banks lying well below the surface of the sea, as well as of atoll-shaped limestone islands whose rims lie many feet above the surface of the sea.

These islands and banks can be interpreted in harmony with most coral reef hypotheses as former atolls. The banks are in the process of building their rim up to sea level once more, and the islands are being acted on by the destructive agents of erosion.

Gray Feather Bank in the west central Caroline Islands is approximately 220 square miles larger than Kwajalein, the largest atoll in the Pacific. The highest part of its rim lies about 8 fathoms below sea level with the average depth of its rim about 15 fathoms. The average depth of the central depression is about 32 fathoms.

Kita Daito and Nauru are two excellent examples of atoll-shaped limestone islands, and there are many others. Both of these probably were atolls in the past and with submergence could be atolls again.

However, not all atoll-shaped islands are necessarily emerged atolls, nor are all atoll-shaped banks necessarily submerged atolls. Some atoll-shaped banks may be submerged atoll-shaped islands on which biohermal growths have become established, but not since their submergence have they grown close enough to the surface of the water to be classified as reefs or atolls. Some atoll-shaped islands may be entirely the result of the subaerial erosion of a raised table reef. In fact, it seems to be normal for emerged limestone islands in the tropics to weather to a saucer-shaped platform with a prominent marginal rim.

Intermediate between the submerged or drowned atolls and the emerged or raised atolls are sea level atolls having stretches of their reefs below low tide level, and atolls having remnants of higher reef (usually forming the core of islands) rising above the level of the present reef flat. Sometimes there are stretches of below sea level reef and remnants of raised reefs in the same atoll. This condition could result from tilting of the atoll, causing erosion of the raised side and continued growth along the drowned side. Westward tilting was given as the reason for this unequal growth in the Marshalls by Tayama (1934), Yabe and Tayama (1937), and Nugent (1946). Another explanation is possible. The warm period following the last glacial period could have been of such short duration that only the more vigorous parts of the reef were able to build up to the temporary high level of the sea.

This level is generally believed to have been approximately 6 feet above present sea level, to which level it rose from a level approximately 300 feet below present sea level, the level reached during the last period of glaciation. Consequently, many parts of the reef might have lagged in growth (or they were low saddles to begin with) and have still not reached even the present altitude of the sea, despite its recent drop of about 6 feet. Following the 6-foot fall of sea level, the parts of the reef which formerly extended higher were planed to successively lower levels, the last being the present reef flat approximately at mean low tide level. Remnants of several of the intermediate reef flats are present beneath and responsible for many existing islands in the Marshalls.

Most of the remnants of raised reef flats in the northern Marshalls observed by the writer are along the northern, eastern, and southern sides of the atolls, whereas the below sea level stretches are mostly on the western side. This may be because the prevailing northeasterly winds and the more prevalent swells from the southern hemisphere provide the northern, eastern, and southern sides with better aeration and more abundant food and, therefore, more vigorous growth than the relatively quiet western side. Once having reached sea level the windward reefs would supply quantities of detritus which would contribute to the broadening of the windward reefs. If this explanation is correct, many of the atolls in the northern Marshalls were near-atolls or semiatolls open on the west side at the close of the postglacial thermal maximum. The relationship between the shape of atolls and the effective winds and currents would have been much more noticeable during such a stage than at present when much of the reef configuration is due to planation.

Local tectonic movement is certainly a logical and probably the true reason for the discrepant altitudes of some emerged atolls and submerged atoll-shaped banks, but it is not true necessarily for all of them. Some topographic features may have had the same relative position for a long time; they merely supported reefs at different times. Fluctuations of sea level during the Pleistocene epoch were great owing to the accumulation and melting of glacial ice. It is also safe to assume that the sea covered and retreated from some areas during the Tertiary because of large crustal adjustments elsewhere. It is possible, therefore, that during periods of high sea level reefs might have become established and flourished on or around topographic highs while other reefs in the same area might have been submerged below their phototropic range and died. During low water periods different reefs might have flourished on the lower points, leaving the higher reefs exposed to the agents of erosion.

Faros.—Faros, although not regarded as a major reef type, are, nevertheless, so characteristic that they should be defined separately.

Kuenen (1950, p. 426) gives the following definition of a faro:

> "Faros are small atoll-shaped reefs with lagoons a few to 30 meters deep, forming part of a barrier or atoll rim. In some instances the rim consists of a row of round or oblong faros with hardly any normal reefs in between."

Some of the examples given by Kuenen have the appearance of being double barriers, but actually they are reefs growing up from both sides of

barrier banks, enclosing a shallow lagoon along the crest of the banks. Another illustration from the Maldive Islands shows atolls whose enclosing reefs are composed almost entirely of faros separated from each other by passages; some of the faros themselves have passages connecting their lagoons with the outside. Other faros are essentially lagoon atolls and are located entirely within the outer ring of faros.

SUMMARY

In summary: 1) the term "reef" has physiographic implications that cannot be ignored if the classification of organic reefs as fringing reefs, table reefs, barrier reefs, and atolls is to be maintained; 2) the reef rock complex consists of both biohermal and detrital facies; 3) organic banks, and organic reefs close to or barely reaching the surface may be mostly biohermal along their upper surface; 4) broad reefs, particularly barrier reefs and atolls, may accumulate a large component of back-reef detritus, lying at or closer to the surface than the more steeply dipping fore-reef detritus; 5) in the present geologic phase, which has followed a fall of sea level, there is a surface of planation across seaward biohermal and back-reef detrital facies alike, resulting in reef flats with an outer zone of biohermal reef rock and a broader inner zone of detrital reef rock; 6) the term "reef rock" is recommended for both biohermal and detrital facies of both organic reefs and banks; 7) other associated detrital facies which do not form part of the near sea level component of reefs, such as lagoon sediments and talus on the submarine slope, were derived largely from the reef although they are not part of the reef, and should be regarded as reef rock to differentiate them from alien sediments.

The more important terms used in this report are defined briefly as follows:

1. Reef—a rocky elevation rising to the surface, or within 6 fathoms of the surface of water.

2. Bank—an isolated underwater elevation on which there is a depth of over 6 fathoms of water.

3. Organic reef—a reef formed by living organisms and their remains. An organic reef may consist of a bioherm alone, particularly if it barely reaches the surface, or if there is a broad reef flat, only the outer edge may be a bioherm, the remainder consisting of detrital materials derived from the bioherm. (A more detailed definition of an organic reef is given on page 389.)

4. Organic bank—similar to an organic reef except that it lies below 6 fathoms of water. The detrital component of organic banks would consist mainly of the skeletons of unattached organisms and debris produced by living organisms. Mechanical fragmentation on banks would be insignificant compared with that of reefs.

5. Bioherm—a growth lattice of organisms whose vertical dimension exceeds the thickness of sediments deposited contemporaneously around it. A

bioherm can be all or part of a bank or reef. A bioherm in the geologic column may be enclosed by detrital reef rock or alien rock. A living bioherm may be partly enclosed or not enclosed.

6. Reef detritus—materials derived from the erosion of an organic reef or bank and from solitary organisms living on it. The amount of detritus derived from an organic bank situated well below the action of waves is small. Organic reefs by virtue of their continuous growth can supply an unlimited amount of detritus. (Inorganic reefs produce small amounts of detritus, the amount depending on the volume of rock lying within the zone of erosion.)

7. Reef rock—rock, consolidated or unconsolidated, forming, or derived from organic reefs and banks. Rock composed of a growth lattice is biohermal reef rock. Rock composed of bioherm detritus or unattached reef dwellers is detrital reef rock. In a lithologic sense, living stone corals and algae are biohermal reef rock.

8. Reef rock complex—the regimen of reef rocks.

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THE SHAPE OF ATOLLS: AN INHERITANCE FROM SUBAERIAL EROSION FORMS*

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ABSTRACT. A theory for the development of atolls is proposed that is essentially a combination of the theory of glacially controlled subsidence of Ph. H. Kuenen and the suggestion by Yabe and Asano that the shape of atolls is controlled by limestone solution forms. Grand subsidence is held necessary for the accumulation of thousands of feet of limestone of shallow water facies beneath oceanic atolls, and glacially controlled fluctuations in sea level provide for periods of subaerial erosion. Existing high limestone islands in the tropical Pacific are weathered to basin-shaped platforms with prominent raised rims and precipitous outer walls. Residual pinnacles of limestone rise above the floor of the central depression. Natural levees of limestone with steep, bare, casehardened (recrystallized) stream-facing walls and gentler soil-covered back slopes occur near the mouths of streams. It is held that these solution forms provide prominences on which might grow the essential features of oceanic atolls such as the annular main reef, coral knolls in the lagoon, and the peculiar arrangement of reefs often found inside the deep passes.

The subject of post-Tertiary fluctuations of sea level is reviewed as a prerequisite to the general thesis. Support is given to the theory that sea level fluctuations of the order of 300 feet due to continental glaciation took place during Pleistocene time, and that these were superimposed on a more gradual and continual lowering of sea level. Thus, each successive interglacial high water mark was lower than the preceding interglacial high water mark, and each successive glacial low water mark was lower than the preceding glacial low water mark. The last significant change of sea level was a fall of about 6 feet to or just below present sea level. The drop of 6 feet is assigned to post-Pleistocene time. Sea level is now rising again.

INTRODUCTION

Since 1837, when Darwin first proposed the theory that barrier reefs result from upward growth along the margin of fringing reefs bordering subsiding volcanic islands and that they become atolls with complete subsidence of the island, many explanations for the growth and shape of reefs have been proposed. These theories are known collectively as the "coral reef hypotheses." Though it is true that most authors have sought to explain barriers and atolls as the ultimate form of reefs, the inclusion of all reef hypotheses under one heading implies more conflict than actually exists. Generally no distinction is made between theories dealing mainly with the foundation of reefs, the growth of reefs, and the shape of reefs. There is a general feeling among investigators at present that atolls are not always formed the same way, and therefore that no one theory can explain all atolls. It is also becoming clear that oceanic atolls have had a long and involved geologic history. The points stressed in different theories are often incommensurable. The problem of the deep foundation is not necessarily the problem of the lagoon and annular reef of the present atoll, and it is futile to argue, for instance, that the glacial control theory of Daly is untenable because it does not explain the great thickness of limestone in some oceanic atolls.

Various attempts have been made to integrate the coral reef hypotheses on the assumption that if no one theory is correct in its entirety, the correct answer must lie in a combination of several of them. To the writer it would seem that each atoll should be studied as an individual, and it is not thought

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that the present hypothesis, believed to be true for the oceanic atolls of the mid-Pacific, is necessarily true for the atolls of the Great Barrier Reef. It seems immaterial whether the first reef-forming organisms beneath an atoll grew as a fringing reef or on a submerged platform, or whether the base was rising or falling at the time. Vaughan, Hoffmeister and Ladd, Umbgrove, Kuenen, and other authors have shown that reefs can become established on bottoms of almost any type, provided they lie within the phototropic and temperature range of corals, and the water does not contain smothering amounts of sand or silt. The present theory assumes that a biohermal growth is started and that sooner or later, whether retarded by a sinking bottom or assisted by a rising bottom, it reaches the surface to form a table reef (pl. 1, diag. 1). The development of the atoll is subsequent process.

Probably the greatest point of dissention among coral reef theorists has been the effect, or even the fact of glacial oscillation of sea level. Some workers have considered it the only possible explanation for some reef features, whereas others have denied its occurrence. Glacial fluctuations of sea level could leave their effects, minor or major, on reefs regardless of whether their foundations were rising or subsiding—and apparently did. Were it not for glaciation during the Pleistocene epoch and the important oscillations of sea level due to the impounding of part of the hydrosphere as glacial ice, the reefs of the world might have an aspect quite different from the one they now have, a view also held by Daly (1915). It is held that some reef types, including atolls and barriers, are growing on subaerial erosion forms, and that without periods of subaerial erosion provided by the low water glacial stages, fringing reefs and table reefs would predominate. Atolls and barriers might be present in regions uplifted and resubmerged by tectonic movements.

Though the present paper is an exposition of a theory to which little attention has been given, the idea is by no means new. Yabe (1942) and Asano (1942) both suggested that reefs in the tropical Pacific are growing on limestone solution forms. Umbgrove (1947) mentioned the possibility but rejected it. The paper draws heavily on observational and experimental data by Hoffmeister and Ladd (1945), and on the writer's own observations of limestone solution forms on Okinawa. Hoffmeister and Ladd concluded that some atoll-shaped limestone islands in the tropical Pacific are not raised atolls, as they have been stated to be, but saucer-shaped platforms formed entirely by solution. They did not suggest that such forms might with submergence be the foundation of atolls—even though these writers proposed the antecedent platform theory. Probably the association of saucer-shaped limestone platforms and atolls might have received serious consideration earlier if the solution forms had been better known. For a paper dealing specifically with limestone solution walls on Okinawa, see Flint, Corwin, Dings, Fuller, MacNeil, and Saplis (1953).

CHANGES OF OCEAN LEVEL

Glacial Eustasy and the Theory of Eustatism

To modern glacial geologists the idea of glacial eustasy (or the fluctuation of sea level due to absorption and release of water in ice caps) needs no

defense; the real problems being the correlation of the glacial stages with the different raised shore lines, and the absolute dating of the periods of glaciation. Calculations of the amount of water stored in the ice caps, and of the amount of water necessary to raise or lower sea level between observed shore lines are of so nearly the same magnitude that they appear correlative. Both lines of evidence suggest that the eustatic difference in sea level was about 300 feet.

However, change of absolute sea level due to some cause other than glaciation seems also to have occurred during the Pleistocene and possibly earlier. The latter appears to have been in the form of an evenly continuous fall of sea level, whereas glacial eustasy was oscillatory. The concept of continuous lowering of sea level has been termed the *theory of eustatism*.

Zeuner (1945, p. 164) discussed the two types of sea level change as follows:

"One of the queer facts of Pleistocene stratigraphy is that the interglacial sea levels were successively lower. Interpreted solely in terms of glacial eustasy, this would mean that in each interglacial less deglaciation took place than in the preceding one, an assumption which does not sound acceptable in view of the evidence for the climate of the interglacials. Some other factor, therefore, appears to have brought about the gradual lowering of the sea level, the fluctuations due to glacial eustasy being merely superimposed on some major cause which depressed sea level progressively throughout the Pleistocene. . . . the ubiquity of the Pleistocene sea levels, which are found at the same height in Australia and America as in Europe, suggests that the sea level during the Pleistocene (and conceivably in the Tertiary also) actually became lower, since it is impossible to regard the rising of the land as taking place at the same rate everywhere, so that the heights of ancient beaches remain the same in distant localities. It appears possible, therefore, that the sea level sank by several hundred meters during the Tertiary and Pleistocene. . . . This is the theory of eustatism, and the most probable cause of the phenomena interpreted by it is a sinking [somewhere] of the bottom of the sea."

Elsewhere (p. 250) Zeuner estimates the lowering of sea level to have amounted to about 70 meters in 600,000 years, or about one tenth of a millimeter annually.

Although the theory of eustatism is not a new idea, explanations for it are still within the realm of pure speculation (Zeuner, 1952, p. 49). Stearns (1945) suggested that subsidence occurred at the close of the Pliocene epoch in the Pacific east of the Sial Line (a line similar in concept to the "andesite line" of earlier writers) owing to collapse or down-bowing of the ocean floor under the weight of great volcanic outpourings. The area west of the Sial Line he regards as part of an epirogenic belt surrounding the subsiding Pacific block in which folds were formed and rose toward the surface of the sea. His theory not only could be offered in explanation of the theory of eustatism, but it attributes the reefs west of the Sial Line to growth on rising platforms and the reefs east of the Sial Line to growth on subsiding platforms.

The possibility that eustatic fall continued throughout the Tertiary and that it resulted from the foundering of one or more ocean floors may draw some support from recent findings at Bikini. Ladd, Tracey, and Lill (1948) reported that shallow water, nonpelagic organisms are present in sediments over 1000 feet below the present surface. This does not preclude foundering of individual sea mounts, but it is what would be expected if large areas of the Pacific floor subsided gradually.

In Georgia and Florida the highest features recognized by the writer (MacNeil, 1950a) as Pleistocene shore lines lie at an altitude of about 150 feet. These were assigned to the Yarmouth interglacial stage. The minus 300 foot mark, which in many parts of the world marks the edge of the continental shelf, submarine benches, and other features is regarded by many as the last and lowest Pleistocene sea level. If the estimate that glacial fluctuations of sea level were of the order of 300 feet is correct, and it can be assumed that the Yarmouth interglacial sea rose to 150 feet above from a level of about 150 feet below sea level, and the last glacial sea fell to about minus 300 feet from close to present sea level, a general eustatic lowering of sea level from the second interglacial stage to the present of about 150 feet is indicated. This figure is not inconsistent with Zeuner's estimate of a general eustatic fall of about 70 meters in 600,000 years.

Regardless of whether change of sea level is held necessary for the growth of reefs, or of how important changes of sea level have been in the development of barriers and atolls, the fact that sea level did oscillate during the Pleistocene seems inescapable.

For other references relating to Pleistocene sea levels see Fairbridge (1950a) and Fairbridge and Gill (1947).

The Last Significant Change of Sea Level

If fluctuation of sea level took place during the Pleistocene epoch, and if the shaping of modern reefs can be attributed to alternating periods of growth and erosion, the most recent shifts of sea level, however slight, take on great significance in determining whether existing reef forms are depositional or erosional features. It would certainly be backward reasoning to assume shifts of sea level beforehand and to interpret reef forms accordingly. At the same time, one risks attributing reef forms to processes not involved if he assumes that no change of sea level has occurred. If there is proof that sea level is now changing, and if significant late equivalent changes of sea level can be demonstrated in remote parts of the world, an explanation that existing reef forms have developed during a stillstand of the sea should be viewed with caution.

Evidence is accumulating from isolated sources of the existence of abandoned shore lines at altitudes of less than 10 feet above present sea level. Fairbridge (1948) believes that three low shore lines can be identified in the Houtman Abrolhos Islands at 2½ feet, at 5 to 6 feet, and at 10 feet above present low tide level. Kuenen (1933) found three similar levels in the East Indies. Stearns (1941) determined the altitude of a shore line in the north Pacific at 5 feet. MacNeil (1950a) estimated the altitude of a late shore line in Georgia and Florida at 6 to 10 feet above sea level. Remnants of a raised reef flat about 5 to 6 feet above the present flat were reported from Okinawa (MacNeil, 1950b). Carter and Sokoloff (1951) found evidence for a terrace 6 feet above sea level in the Chesapeake Bay region. Raised terraces were found by Cloud (1952) in the Gilberts. There are many others from practically all coastal regions of the world. There is no current agreement on the absolute age of the low shore lines, or on whether they represent one

or several minor advances of the sea. Without exception, however, they have been regarded as post-Pleistocene, presumably representing one or more post-glacial periods of warmth.

Atolls have been considered a poor place to study raised shore lines in spite of the fact that they may have been influenced greatly by glacial eustasy. Limestone solution takes place very rapidly within the intertidal zone and just above it, as evidenced by the well-known phenomenon of wave-cut nips and mushroom stacks. Few points on atolls rise more than a few feet above high-tide level, and practically all reef surfaces lie within or below the intertidal zone.

However, in the northern Marshalls many indurated rock platforms lying above the level of the present reef can be interpreted as remnants of higher reef flats. These platforms underlie and are apparently the reason for the existence of many islands. Denudation of unconsolidated materials from islands by storms has revealed platforms as much as 100 yards wide, standing several feet above the present reef flat. The platforms appear to be planed surfaces, similar to the present reef flat, but rougher owing to the weathering into relief of coral and algal fragments. The rock of the high platforms cannot be distinguished from the rock of the present reef flat in either texture or composition.

The highest rock platforms observed were found to lie approximately 5 to 5½ feet above the present reef flat. Platforms were observed in other places at practically all altitudes between 5½ feet and the present reef flat, although the greatest number probably fall between 2½ to 3 feet above the reef flat. It can be assumed that these rock platforms are remnants of older reef flats, and that they were planed at the same relative position as the existing flat (approximately at mean low tide, the inner edge of the flat being close to high low tide). Evidence in the northern Marshall Islands thus points to a late stand of the sea close to 6 feet above present sea level. This agrees closely with a shore line that has been observed in widely scattered regions, and has been assigned to the post-Pleistocene interval. There is also evidence for an ensuing drop of sea level during which at least parts of the reef were planed to successively lower levels.

It is probably safe to assume, therefore, that the last significant change of sea level was a downward shift from an altitude about 6 feet above its present one with at least one pause at an intermediate level. There is a strong local evidence, but as yet inconclusive on a world-wide scale, that the lower limit reached was several feet below present sea level (Bradley, 1953).

The Present Trend of Sea Level

The present trend of sea level is known by accurate tidal measurements over the last century (Gutenberg, 1941; Marmer, 1948). During that period mean sea level has risen about 3 inches. This agrees with less documented but probably reliable evidence that glaciers in general have been melting since the 19th century. Flint (1947, p. 499) says:

"Data gathered by the International Commission of Snow and of Glaciers have shown that, wherever information has been obtainable, glaciers reached a maximum in the nineteenth century and since that time have been shrinking at a rapid rate."

There seems to be no evidence of any significant changes of sea level during the preceding 30 or more centuries and it seems likely that sea level has remained more or less stationary, or with only minor changes during that time. This certainly allows ample time for sea level erosion, especially of intertidal limestones in the tropics, and offers a reasonable explanation for the apparent planation of most of the world's reefs.

Carter and Sokoloff (1951) comment on the period of nonactivity as follows:

"We have by reading, personal interview, and by correspondence inquired into such questions as the degree of weathering of volcanic ash at Pompeii, any evidence of sea level changes from docks and boat works in Greek, Roman, Phoenician, and earlier times, and so forth. The results are generally negative. We have obtained no clear evidence of widespread changes of sea level of any magnitude within the past 3,000 years. Meaningful soil formation evidence is almost unobtainable. Soil materials have accumulated, but soil horizons seem not to have developed. While the soil information is poor, we consider the sea level information significant. It seems improbable that a sea level stand of 12 or even 6 feet is likely to have occurred as recently as 2,000 or 3,000 B.C. and not left a clear mark in the Mediterranean world. The little evidence we have suggests only a small sea level rise."

The most we can say from such evidence is, therefore, that sea level during the postglacial period seems to have stood about 6 feet higher than at present, but that for several thousand years apparently it has been close to its present level. We know that sea level is rising now and has risen about 3 inches in the last hundred years.

ATOLLS AND THEIR FOUNDATIONS

An atoll is a reef. The fact that it is annular requires explanation, but its annularity is not necessarily a condition related, in the case of oceanic atolls, to the great thickness of limestone beneath it. The term reef in this discussion is restricted to the last continuous growth of reef-forming organisms on lifeless material. Whatever the reef grows upon is the foundation.

The foundation of an atoll may consist of 1) an older series of reef rock separated from the present series by an erosional disconformity, 2) limestones of other types lying either conformably or unconformably below the present reef, or 3) alien rock such as sedimentary non-calcareous or volcanic rock, or 4) any combination of the preceding.

The definitions given here may be stricter than some, but the writer believes this concept is necessary to clear understanding of how oceanic atolls are formed and what they rest upon. If the limestone column beneath an oceanic atoll can be shown to consist of reef rock of several ages, the writer would call it a succession of reefs (in the absence of information to distinguish reefs from banks). However, zones of reef rock lying below the last erosional unconformity are part of the foundation on which the recent reef is growing. A succession of reefs is no different in a stratigraphic sense from any other succession of similar deposits. Each reef depended on conditions prevalent at the time of its deposition, not on the composition of the foundation on which it grew.

Great columns of Tertiary limestone underlying Pacific atolls can only be accounted for by continued subsidence, either of the entire Pacific basin or of individual sea mounts. Drilling at Bikini has shown that shallow water

organisms are present in the limestones at least a thousand feet below the present level of the sea, suggesting that the accumulation of the limestones took place at shallow depths. However, we do not know at present whether the tops of the structures were atolls in the past, or whether throughout most of the Tertiary time they were table reefs or banks. At times they might not even have been inhabited by corals or algae but might have been built upwards by the accumulation of foraminifers, mollusks, and other solitary forms.

Other sea mounts lying at depths below the surface comparable to the top of the igneous basements of atolls are not covered with appreciable thicknesses of calcareous deposits (see Carsola and Dietz, 1952). This could be explained in one of several ways: 1) the bare sea mounts were never close enough to the surface to support biohermal growth; 2) they subsided so rapidly that phototropic animals and plants could not maintain proximity to the surface; and 3) they are either located outside the normal temperature range of corals or are affected by cold currents that prevent the growth of corals and coralline algae.

CORAL REEF HYPOTHESES

The most recent, and probably the best summaries of coral reef theories are to be found in a short paper by Ladd and Tracey (1949), in the chapter on coral reefs by Kuenen (1950) in his textbook, *Marine Geology*, and in a paper by Cotton (1948). The main points on which the various theories differ concern the shape and composition of the foundations, their position and stability with respect to sea level, and the relative importance of organic growth and solution in producing the annular shape of barriers and atolls.

Hoffmeister and Ladd (1944) summarized the more important theories according to whether or not they required a change of sea level:

(1) Those which require a change of sea level relative to the reef foundation.

a) Darwin's theory of a sinking land area and consequent rising sea level. Under these conditions, it is stated, the corals grow upward and outward, converting fringing reefs into barriers and finally into atolls. Dana and Davis strongly supported this theory.

b) The glacial-control theory ably developed by Daly. It postulates rising sea level due to the return of water to the sea following periods of glaciation.

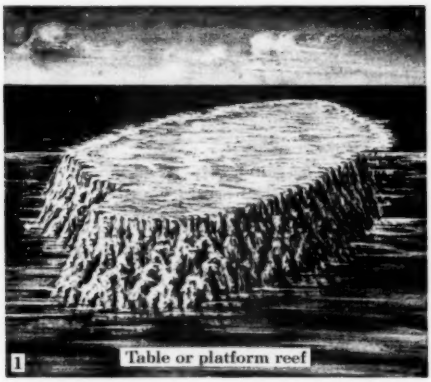
c) Vaughan's theory of pre-existing flats formed by various processes, followed by gradual submergence caused by crustal movements or rising ocean level.

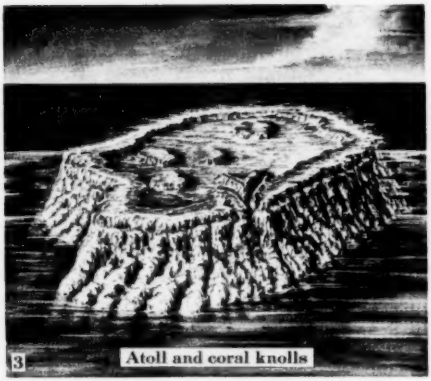
d) Semper's theory of reef formation on a rising submarine volcanic mound.

(2) Those which hold that reefs may develop without change of sea level relative to the reef foundation.

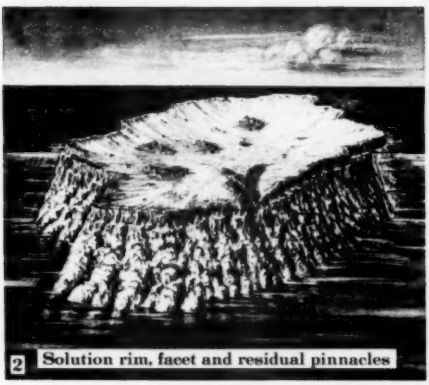
a) The Rein theory of the accumulation of organic deposits on still-standing submarine summits to serve as foundations for atolls.

b) The Murray theory, which extends the Rein theory, stating that





SUBMERGENCE



EMERGENCE

SUBMERGENCE

DIAGRAMS SHOWING SUPPOSED DEVELOPMENT OF ATOLLS AND FAROS ON SUBAERIAL EROSION FORMS

DRAWN BY JOHN R. STACY

atoll lagoons are enlarged by solution as the reef grows outward on its own talus material.

c) Agassiz's theory for the formation of atolls by solution operating on existing limestone masses and the formation of barrier reefs by growth of corals on platforms made by marine erosion without change of sea level.

d) The theory of Wharton, later expounded by Gardner, that corals grow upon foundations made by submarine planation of volcanic islands.

e) The antecedent-platform theory as presented by Hoffmeister and Ladd, which holds that any bench or bank — even one not "smooth"—that is located at a proper depth within the circumequatorial coral reef zone can be considered a potential coral reef foundation and that, if ecological conditions permit, a reef could grow up to the surface without any change in ocean level . . . . . sea level change may stimulate reef growth, but . . . is not essential for the formation of a flourishing barrier or atoll.

Stearns (1946) classified the coral reef theories according to the type of foundation they required:

A. Intermittently subsiding foundations	(Darwin (Dana (Davis
B. Rising foundations	(Semper (Guppy
C. Still-standing foundations	(Rein (Murray (Wood-Jones
(1) Truncated or partly truncated by erosion	(Wharton (Tyerman (Bennet (Guppy (Agassiz
(2) Truncated or partly truncated but with fluctuating sea level	(Daly (Stearns

Although all of the reef hypotheses have stressed the importance of the position of foundations relative to sea level, there has been diverse opinion on what the position was. All have visualized some sort of alien platform or prominence beneath the limestone column of atolls, but opinion has differed on whether the limestone is entirely the result of reef growth or may be limestone of other origin. A number of theories state specifically that atolls grow on smooth or truncated platforms, whereas other theories apparently considered the point unimportant and assumed that atolls could grow on platforms of any shape, with organic growth, aided by outside physical conditions, being the controlling factor in the development of the annular shape.

Only Yabe (1942) and Asano (1942) (whose works published in Japanese were unknown to westerners until recently) seem to have given serious consideration to the possibility that some atolls are atolls because their platforms are atoll-shaped. As will be discussed later, the author also feels that some oceanic atolls, specifically those of the Marshall Islands, had their lagoons and annular rims prefashioned from older limestone or reef rock by processes of subaerial erosion that are still operating in the tropical and subtropical Pacific (pl. 1).

The application of glacial eustasy by Daly (1915) to explain the growth of coral reefs in his glacial-control theory provided a better explanation for the origin of lagoons and their nearly uniform depths (particularly those having different levels of uniform depth) than the continuous subsidence theory of Darwin or any of the theories that require a stillstand of the sea. However, some of the conditions that Daly believed operated with glacial fluctuations seem at this date to follow rather dubiously. One of the main arguments between Daly and Davis was whether the low Pleistocene sea levels were of sufficient duration for the complete planation of reefs, a requirement that now seems both unnecessary and unlikely. Daly believed that countless corals were killed during the glacial periods by the seas growing cold and their content of mud increasing due to exposure of more land areas.

Daly also believed that fringing reefs existed in pre-Pleistocene times but that barriers and atolls first came into existence during the Pleistocene as a result of glacial eustasy. The latter may be partly true, but even if, as here maintained, subaerial erosion is one of the most important factors in producing atoll-shaped foundations, and fluctuation of sea level might account for the great abundance of them, it is by no means certain that all atolls originated as a result of glacial eustasy. Tectonic movements could also elevate and submerge reefs and there is reason to suppose that throughout Tertiary time atoll-shaped limestone islands came into being as a result of subaerial erosion during periods of crustal adjustment.

More recently Kuenen (1947), realizing that grand subsidence must have occurred to account for the tremendous thickness of limestone beneath oceanic atolls, but believing there are too many points that cannot be explained by subsidence alone, combined the subsidence theory and glacial eustasy into what he calls "the theory of glacially controlled subsidence." Some of Kuenen's postulates seem no more attractive than some of the points that he believes argue against other theories. He suggests that chemical erosion, which would produce no smothering fines to kill corals, removes all objections to the low level planation of reefs during the glacial low water periods. He says:

"Obviously the amount (of erosion) is open to considerable doubt. The writer believes, however, there are sufficient grounds for allowing the possibility of total abrasion of pre-existing reefs during each of the successive ice-ages, but he is inclined to assume that considerable portions remained here and there. The fact that interglacial sea level was probably higher by a few dozen meters than the present remnants stick up anywhere from present reefs, is a strong indication that elevated rims underwent considerable reduction during the time available for abrasion and denudation."

However, Kuenen himself (1933) described three raised atolls on the Borneo shelf, Muaras, Maratua, and Kakaban, in which all stages of erosion are suggested. Kuenen described a parallel ridging on Maratua that he ascribed to parallel reefs, not solution, although he thought some modification of the growth forms by solution might be possible. It is not obvious from the published illustrations how much the parallel ridges on Maratua resemble the solution ridges on Kita Daito Jima (pl. 8), and it would be helpful to know more of the composition of the limestone. At any rate, Muaras, Maratua, and Kakaban must be regarded as eroded atolls, not eroded table reefs, and therefore referable to the writer's stage 4 (pl. 1) in atoll genesis.

Actually many remnants of what are believed to be post-Pleistocene reefs extend above the level of present reefs in the northern Marshalls. However, interglacial reefs have been exposed to not one but two or more lengthy periods of erosion. No one really knows whether the interglacial reefs ever built up completely to the level of the interglacial seas, and they could have weathered to irregular forms below present sea level during the glacial periods. Until enough closely spaced shallow drilling is done on atolls to determine whether post-Pleistocene reefs are growing on smooth or irregular platforms, we can only speculate on their shape.

Mean sea level measurements over the past hundred years indicate that sea level is rising again (Marmer, 1948). Yet, remnants of raised reef flats, having at least the semiprotection of a few feet of storm-cast sand and boulder detritus, form the core of islands in the northern Marshalls. The writer suggests that present reefs are planed as much as they are because sea level has fluctuated close to its present level for several thousand years. If sea level had fallen steadily since the last thermal optimum to the minus 300 foot level, the limit it is believed by some to have reached during the last Pleistocene glaciation, it is extremely doubtful if sea level solution, as rapid as it is in the tropics, could have kept up with the fall. Irregular rims similar to those of Maratua and Kakaban probably would have resulted.

Atolls on continental or even large insular shelves may present special problems. Even here the possibility that subaerial erosion forms may be responsible for the shape of reefs cannot be ignored; in fact, it is strongly suggested by the islands of Muaras, Maratua, and Kakaban on the Borneo shelf. Another hypothesis was suggested by Fairbridge (1950b). With examples from the Great Barrier Reef, he suggested that patch reefs (small table reefs) are influenced by prevailing winds to assume a crescentic form, which he called the "horse shoe form," and that a large platform reef might develop from the horseshoe form either by: 1) simple thickening of the crescent to form a "horse hoof form" and eventually an oval platform, or 2) by the growth of two long horns at the ends of the horseshoe to form a U-shape reef or "semi-atoll," next, closing of the horns on the leeward side to form an atoll, and finally, filling in the lagoon to form a "great reef platform" (see Fairbridge, 1950b, p. 358, fig.7).

THE SUBAERIAL EROSION THEORY

The theory that in the writer's opinion best explains the atolls of the northern Marshall Islands combines the essential features of several theories

PLATE 2

A. Limestone rim along eastern side of Eua, Tonga. (after Hoffmeister and Ladd)

B. Limestone rim from the surface of the central depression, Eua, Tonga. (after Hoffmeister and Ladd)

previously proposed. Though it recognizes the importance of organic growth during periods of submergence, it places at least equal importance on the role of subaerial erosion in fashioning the lagoonal depressions and annular rims of atolls. This idea, which was first advanced by Yabe (1942) and shortly thereafter by Asano (1942) as a result of observations in the South Seas, draws support from the writer's own observations of limestone solution features on Okinawa, and from laboratory experiments by Hoffmeister and Ladd.

Kuenen (1947), in order to account for both the thickness of limestone beneath oceanic atolls and the features above 100 meters depth that are best explained by sea level fluctuations, combined the subsidence theory of Darwin and the glacial control theory of Daly into what he called the theory of glacially controlled subsidence. Both Kuenen and Daly, and several others whose theories required fluctuations of sea level, held that low level planation of reefs, and even the outright killing of reefs, took place during the low sea level stages of the Pleistocene. The present theory upholds subsidence and glacial eustasy but maintains that emerged limestone platforms will weather with the formation of marginal rims and central depressions (pl. 1-2), and that emerged irregular limestone islands will have their topography accentuated by the initial stages of weathering (pl. 1-4).

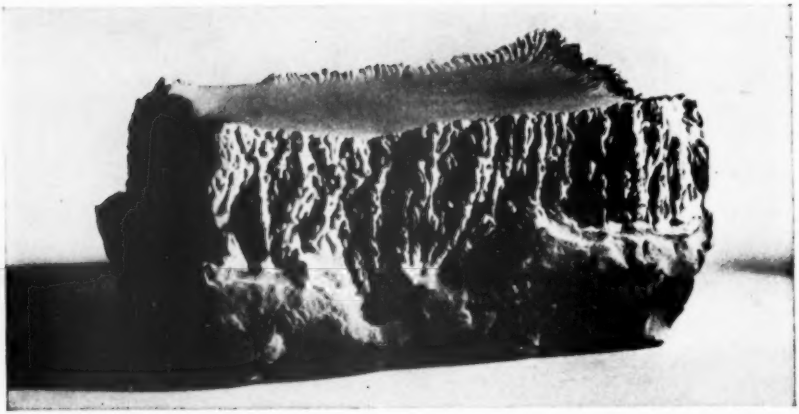
Long weathering will reduce any limestone to base level, but the glacial lowerings of sea level were of comparatively short duration. Solution of limestone takes place actively within the intertidal zone as evidenced by sea level nips and mushroom stacks. The fall of sea level accompanying the accumulation of glacial ice is believed, therefore, to have been too rapid for contemporaneous sea level abrasion at all stages, while the duration of the low water stage is believed to have been too short for the complete subaerial erosion of the exposed limestones.

While grand subsidence is prerequisite to Kuenen's theory of glacially controlled subsidence, to which the author's theory is corollary, it is not thought to have significant bearing on the shape of atolls. Indeed, it seems to this writer that the lagoon and rims of atolls are no more related to the limestone column beneath them than the shape of living reefs on the Florida keys is related to the Tertiary formations of Florida.

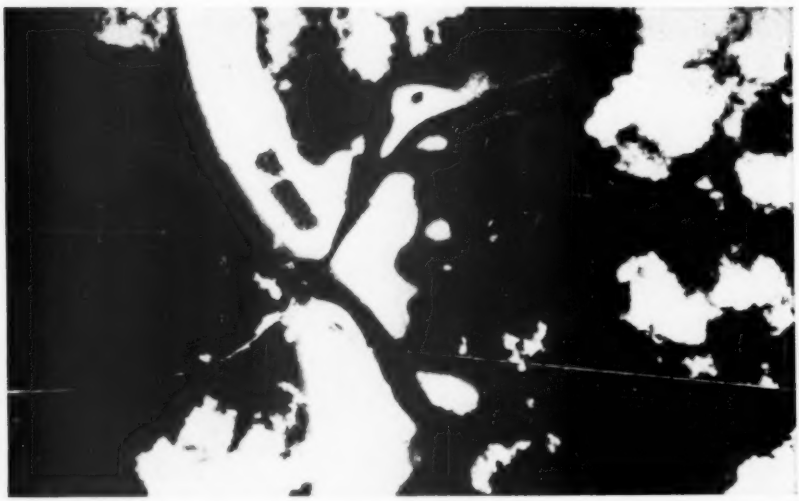
Daly suggested that before the Pleistocene epoch only fringing and flat (table) reefs existed. Atolls he regarded as a result of glacial eustasy. The present theory also holds that emergence and subsidence (which took place almost rhythmically during Pleistocene time) is necessary for the formation of oceanic atolls. However, this does not exclude the less frequent tectonic emergences and subsidences that might have occurred before Pleistocene time.

When it is realized that reefs can and do grow on foundations of any type, that the shape of reefs can be controlled by the shape of their platforms as well as by existing physical conditions (including submarine slides and falling away of parts of the reef (Fairbridge, 1950c)), that reefs are growing on both rising and subsiding bottoms, that subaerial erosion of limestone can produce reeflike forms and accentuate the form of elevated reefs, and that

PLATE 3



A. Solution forms produced on a block of Solenhofen limestone placed under a shower of dilute hydrochloric acid. (after Hoffmeister and Ladd)



B. Bock Channel, Ujae Atoll, northern Marshalls. Elongate reefs along the sides of the deep forked channel suggest limestone walls near the mouth of streams.

major fluctuations of sea level took place during the Pleistocene epoch resulting in several resumptions of organic growth on a series of inherited topographies, it becomes apparent that it is necessary to interpret the history of each atoll separately instead of trying to explain all atolls by a single theory.

The present explanation of the mid-Pacific atolls begins, therefore, with the assumption that at the close of Tertiary time thick subconical deposits of reef rock, capped by living reefs, extended to the surface from many sea mounts.

Miniature Atoll-shaped Block Produced from Solenhofen Limestone

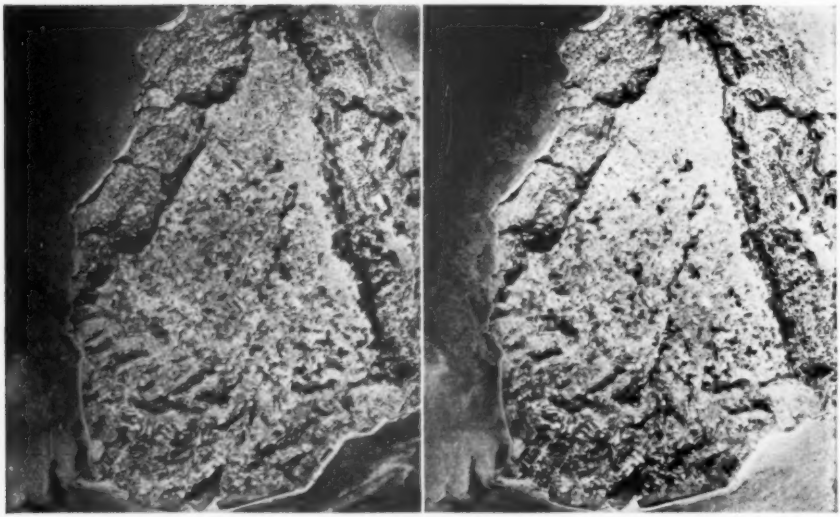
Hoffmeister and Ladd (1945) compared the rampartlike limestone walls observed by them on islands in the southwest Pacific with a similar form that they had produced in the laboratory from a slab of Solenhofen limestone placed beneath a shower of weak acid (pl. 3-A). Similar raised rims had been reported along the edge of flat-lying joint blocks of limestone by Smith and Albritton (1941). The similarity of the forms produced both naturally and in the laboratory is too close to be coincidental, and it seems unlikely that any cause other than solution can be responsible. Hoffmeister and Ladd, and Smith and Albritton attributed the rims to solution and concluded that an initial slope of 3 to 6 degrees is the controlling factor; the rims form along the upslope edge. Hoffmeister and Ladd did not relate the limestone rims to the formation of atolls, but rather sought to show that many of the so-called raised atolls are really solution features. They believed such rims might be taken to indicate tilting of the islands, inasmuch as dips of several degrees seem to be necessary for their formation.

However, the speed of runoff, controlled by slopes on the limestone, is not the only factor involved in the formation of limestone rims, and on Okinawa it might be doubted that it is the most important factor. The point was raised by Smith and Albritton (in Hoffmeister and Ladd, 1945, p. 815) that prevailing winds may modify the normal relationship between runoff (and solution) and slope by retarding the speed of runoff on windward surfaces.

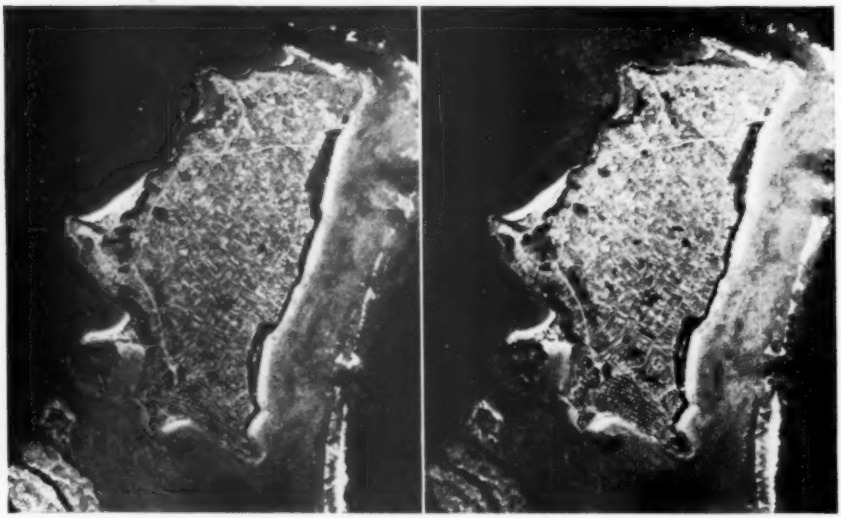
Casehardening and Subsoil Solution

On Okinawa the writer and other members of the U. S. Geological Survey found that all exposed limestone surfaces tend to become hard and dense on the outside, owing possibly to recrystallization by alternate wetting and drying. Casehardening is characteristic of steep limestone cliffs and of the sharp rims commonly found along their crests, although low exposed humps may be similarly hardened. On the other hand, limestone beneath a soil mantle is usually of no more than normal bedrock hardness, and frequently is rotted softer than the normal bedrock. Solution beneath a soil mantle takes place comparatively rapidly, probably aided by humic acids, with the result that some soil-covered areas are underlain by limestone residues to considerable depth. The two processes result in the formation of dense limestone walls, often with knife-edges, along the steep exposed surfaces, and the gradual wasting away of the adjacent limestone under a sloping soil cover.

PLATE 4



A. Takabanare-shima, off eastern Okinawa. The limestone-capped plateau has developed a marginal rim.



B. Ike-shima, off eastern Okinawa. A prominent limestone rim is developed on the lower eastern side.

Therefore, even though rims and facets may be formed on clean blocks of limestone wholly as a result of solution by runoff water, on islands the casehardening of exposed surfaces and the much accelerated solution of limestones under a soil cover may in time become much more important. Once a surface depression is formed, underground drainage may play a still more active part in enlarging it and reducing the central area to general base level.

Differential Weathering of Limestone on Okinawa

Photo-reconnaissance of Okinawa during World War II revealed that several of the larger streams had what appeared to be natural walls along their banks. The writer and others subsequently examined these features and found that they were about 80 feet high at places and were composed of horizontally bedded limestone. More detailed study of the limestones of the island showed that walls are not restricted to the banks of streams, but that many exposed limestone faces have rampart edges of appreciable thickness and height (pls. 4-7). These can be classified separately as follows:

Natural stream embankments.—Some of the streams in southern Okinawa (pls. 5-A, 5-B, and 7-A), the Bisha Gawa (or Hiza Gawa), the Chatan-gawa (or Sada-gawa), the Shiring-gawa, and others, have high natural embankments, in places exceeding 80 feet in height and over 200 feet in width at the base. The sides of the embankments bordering the streams are bare limestone faces, hard enough to make a hammer ring when struck. The sides of the embankments facing away from the streams are more gradual slopes, usually with a soil cover that thickens towards the base of the slope. The rock on the back slope may be relatively soft and in at least one place is hand-quarried for gravel.

Fault scarps with rampart edges.—Many faults cross the island of Okinawa. By far the most obvious, however, are those that cut the plateaus of Pliocene and Pleistocene limestone in the southern peninsula (pl. 7-A). Some small islands off the coast of Okinawa (pl. 4-A and B) appear to be fault blocks. The majority of the major faults are of the order of 300 feet displacement and have steep or sheer sides. The exposed limestone face is very hard. At the top of the exposed face is an irregular knife-edge or rampart 10 to 25 feet high, also composed of very hard limestone. The surface sloping away from the fault scarp on the upthrown side is soil covered. Small limestone pinnacles may extend above the soil on the back slope, and at places where the soil has been eroded recently, the limestone shows a very irregular surface. Windows often expose the underlying clay formation, at places not more than 200 yards back from the fault scarp.

Remnant edges of the upthrown sides of faults.—In regions where the limestone formations have been almost completely eroded away, thin elongate ridges of limestone are common. It can be shown by tracing the ridges into areas of lesser solution that they are remnants of the upthrown sides of faults. The underlying soft clay formation is commonly exposed beneath the limestone ridges, whereas the downthrown side consists of limestone residue to some depth. Preservation of the upthrown side is just the opposite

PLATE 5

A. Limestone walls along the lower Hiza-gawa (Bisha-gawa), Okinawa. (Stereo-pair) The walls are about 80-90 feet high and about 200 feet wide at the base.

B. Limestone walls along the lower Chatan-gawa (Sada-gawa) (top), Okinawa, and along a smaller stream (bottom).

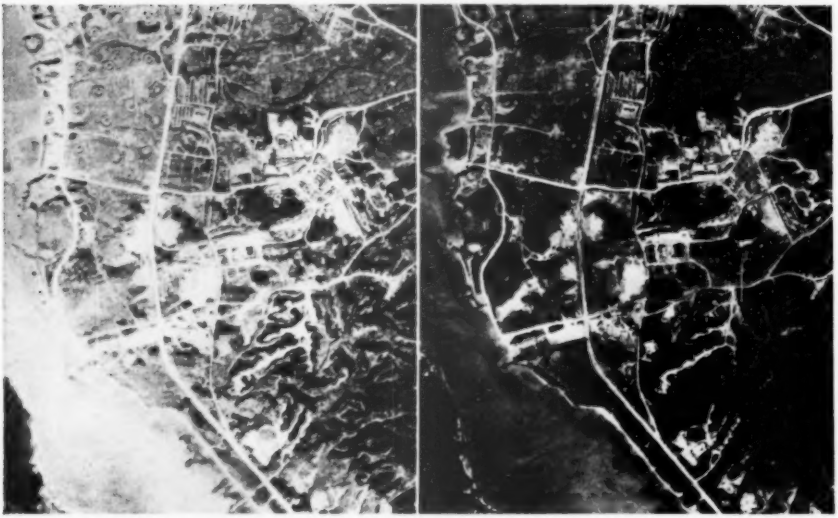
of the condition common in temperate zones where the protected downthrown side resists erosion longer. Obviously on Okinawa the casehardened upthrown face of the fault remains as a remnant, whereas more persistent water or acids in the soil completely leach the buried side.

Ramparts at the edge of limestone terraces.—Well-developed terraces, presumably wave-cut and of Pleistocene age, are found in the areas of limestone terrain in southern Okinawa and on Ie Shima, an island lying off the west coast of Okinawa. Platforms composed of limestone are found at several levels extending from present sea level to an altitude of about 100 meters or somewhat over 300 feet. The lower terraces are incised in Pliocene limestone. The highest platform at about 100 meters is composed of Pleistocene limestone, usually containing large heads of coral in growth positions, and presumably is close to a former level of fringing reefs. The high platform almost certainly has been modified by subaerial erosion, but appears to have remained above the level of subsequent wave planation. All of the terraces, including the highest platform, have well-developed rampart edges at one place or another. The ramparts or rims are usually 8 to 12 feet in height and about the same width at the base. The rim of the 100 meter platform is composed of partly coralliferous limestone, but the rim along the lower terraces is mostly detrital limestone. There is no preponderance of coralline algae in them to indicate they are even partly algal ridges similar to those found on many living windward reefs. The outer face of the terrace scarp is composed of hard limestone. The top surface of the terrace is covered with soil and frequently slopes away from the edge to a level as much as 20 feet or more lower. Where exposed in quarries the limestone below the soil cover shows a very irregular pinnacled surface, apparently due to solution. At many places the inner extension of the terrace consists only of limestone residues, particularly where it terminates against phyllites and quartzites of Paleozoic age.

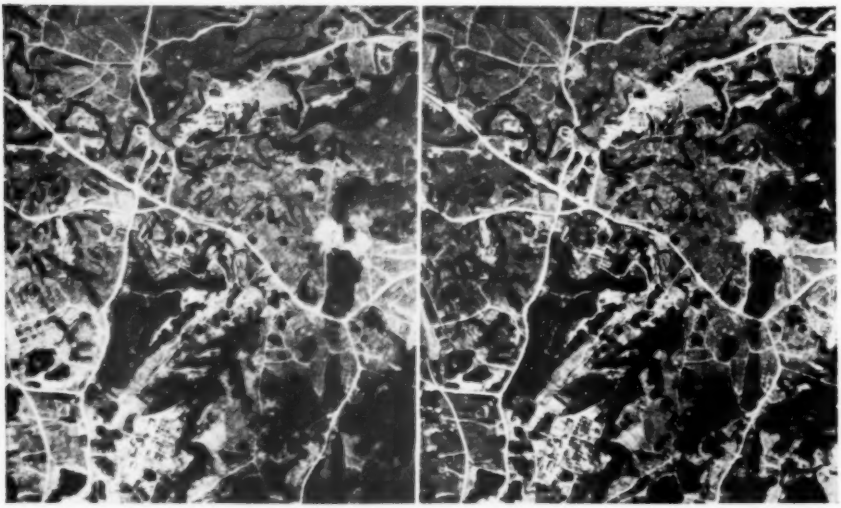
Hoffmeister (1930) described similar rampart edges along raised fringing reefs in the tropical Pacific, and he ascribed the ramparts entirely to solution. Kuenen (1933) discussed Hoffmeister's paper along with papers by others who attributed the features entirely to growth, but arrived at no firm conclusion.

Pinnacles and pipes.—A rather extensive area of solution extends across the southern peninsula in an easterly direction from the vicinity of Kadena to Katchin Hanto, a peninsula of the east coast that marks the northern side of Nagagusuku Wan (Buckner Bay). Within this zone a number of very large residual limestone pinnacles can be seen (pl. 6-A and B, pl. 7-B), although several of the largest are being quarried. One of the easternmost of the pinnacles (pl. 7-B) is really a hollow pipe, and apparently was a sink hole on an old limestone plateau. All of the pinnacles, including the pipe, have a horizontal zonation. They are composed of detrital limestone in the lower part, above which is a zone containing abundant algal nodules that show the pinnacles to be remnants of an extensive bedded limestone. Several of the highest pinnacles are capped by a third zone, elsewhere eroded, containing a high percentage of coral heads. A crack that apparently developed along a common bedding plane was observed in three closely situated pinnacles in

PLATE 6



A. Residual limestone pinnacles, possibly remnants of former stream walls, southern Okinawa. The highly dissected area in the lower right is in sandy and gravelly limestone residues which zone passes beneath the zone of purer limestones to the north.



B. Residual limestone pinnacles near the upper Hiza-gawa, southern Okinawa.

the central part of the area. All exposed surfaces of the pinnacles are extremely hard, but quarrying revealed that the central part of some was softer. The pinnacles probably had their origin as areas of induration early in the dissection of the old limestone plateau, either as open cracks, cavities, or sink holes. A rough alignment of the pinnacles within a narrow belt suggests that they represent either an induration of the walls of a line of sink holes along an old subterranean drainage, or an old age expression of stream embankments.

The rim of the pipe, or "fossil sink hole" (pl. 7-B), stands nearly 100 feet above the level of the surrounding country. The inner walls of the pipe are hard and stand nearly vertical. The outer slope of the pipe is steeper on the west side where it is 45° or more, and more gradual on the east side where it is 25° or less. Soil covers most of the eastern slope, but a few irregular rock projections are present. The lower slope on all sides is covered by soil and limestone residues.

All of the features described above show two main characteristics: 1) steep exposed surfaces that become casehardened and stand in relief, and 2) flat surfaces and gentler slopes that develop a soil cover and gradually waste away.

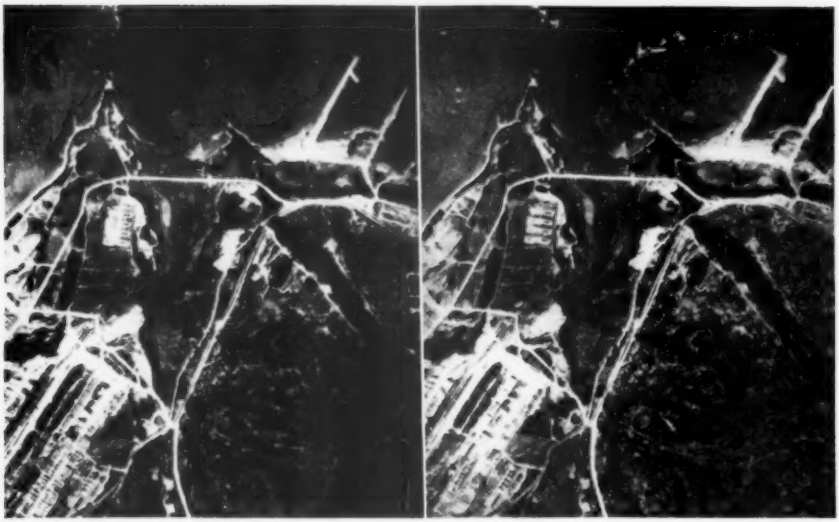
Application of Subaerial Weathering Processes to the Preformation of Atolls

The first implantation of algae, corals, and other reef-building organisms on any particular platform or foundation is not influenced by subaerial weathering processes, nor is it, strictly speaking, a step in the formation of an atoll. Bioherms can grow on any suitable platform, provided depth, temperature, and other factors are right. They could grow to any shape on such a platform, but their climax would be the formation of a flat-topped fringing or table reef (pl. 1-1).

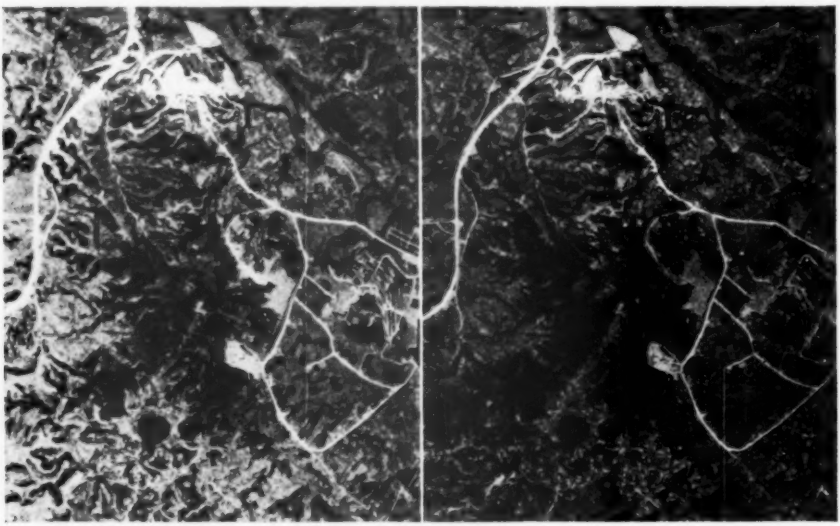
The emergence of a table reef would immediately subject it to weathering processes that could fashion it into a saucer-shaped platform (pl. 1-2). The emerged flat might first be subjected to direct solution by meteoric water, resulting in the formation of a solution facet and raised rims. In time the steeper exposed sides of the emerged reef would become casehardened, giving them even greater resistance to erosion, and a soil would gradually form on the central facet, the humic acids in it hastening the solution of the limestone below. Minor details of relief on the original platform as well as the porosity of the rock might determine whether ponding and subterranean drainage or well-developed surface drainage might result. Inasmuch as surface drainage on the limestones of oceanic islands is practically unknown at the present time, it is probable that drainage went underground early, if not immediately after the emergence of the reefs. Development of subterranean channels would in time honeycomb the emerged reef rock and assist the subsoil solution in reducing most of the central area to sea level.

The assumption of open surface drainage on raised limestone islands might be regarded by some as a weakness in this theory. Open drainage on Okinawa appears to have resulted from the collapse of the roof of a subterranean stream flowing on a clay formation underlying the limestone, presumably

PLATE 7



A. Limestone walls along Shiring-gawa, southern Okinawa. The sharp point is Kuzi-saki. The high wall to the right is the fault scarp known as Kakazu ridge. A knife-edge is developed along the upthrown side.



B. Residual limestone pinnacles near Kanekadan (left) and Kawasaki (right). The pipe-shaped pinnacle near Kawasaki is believed to have been a sink hole whose walls became recrystallized and remained while the surrounding limestone terrain was largely reduced to residue.

as a line of eventually coalescing sink holes. Some subterranean streams remain mostly concealed, but their course is revealed at intervals by sinks. It is suggested that water percolating downward through the porous structure of an island composed entirely of limestone flows laterally at sea level, and may develop well-defined channels at this level. Both the stream and passage might develop from the ultimate collapse of such a channel.

Few atolls or barriers have had their lagoons sufficiently well charted to show drainage patterns. A few atolls are complete atolls; that is, they have no passages through their reefs whatsoever. Many others, such as Pokak in the northern Marshalls have very small passages. On the other hand, there are numerous atolls with passages of approximately the same depth as the deepest part of their lagoons, and a very few with passages deeper than the deepest part of their lagoons. American Passage in the almost-atoll of Vanua Mbalavu in the Lau Archipelago, Fiji, is one of the better-known deep passages.

Recently Emery (1948) published a very detailed hydrographic chart of Eniwetok Atoll in the northern Marshalls. The single deep passage of Eniwetok has one small area approximately as deep as the deepest part of the lagoon (over 32 fathoms), although most of the passage is between 28 and 32 fathoms. The passage forks to form two well-developed channels along both sides of a wedge-shaped reef about a mile and a half inside the main reef. The southern leg of the fork is the deeper and there is a good alignment of elongate troughs of between 28 and 32 fathoms bending first to the south and then gradually around in the direction of the deep central part of the lagoon. Emery suggested that a stream which drained a lake in the central depression probably flowed through the deeper channel and passage. The suggestion of a stream flowing through the passage seems sound enough, but the former existence of a central lake might be open to question. A lake is suggested by the gradual shallowing of the lagoon towards the sides. This might be original, but it might also be due in part to the accumulation of detrital materials from the present reef, especially along the windward side.

The irregularities of the lagoon floor of Eniwetok show features strongly suggestive of solution, and some of them might be interpreted as casehardening phenomena. Coral knolls, which are abundant in the lagoon, may well be growing up from pinnacles left as remnants during a period of subaerial erosion (pl. 1-2 and 3). Both the wedge-shaped reef at the inner end of the main passage, and the triangular reef (Bogen I.) north of the passage suggest casehardened stream embankments that were since modified by growths of coral and accumulations of detritus.

Reefs and islands just inside the major passes are common in the northern Marshalls (South Pass, Likiep; Tolap Pass, Ailuk; Bock Channel, Ujae; and several passes of Kwajalein). These reefs are often elongate and arranged along the edge of deep channels (pl. 3-B). The suggestion is strong that these reefs are growing on limestone walls like those bordering the streams of Okinawa (pl. 5-A and B).

Complete atolls, even though they have no gaps in their reefs that could be interpreted as drainage exits, might nevertheless have had portal exits or

PLATE 8

Rim and wall facing central depression on the west side of Kita Daito Jima. This island is believed to be a raised atoll. Solution rims along the raised annular reef might be the foundation of future faros. (Photo by R. A. Saplis)

springs along their sides. In fact, the prevalence of underground drainage and springs on existing limestone islands suggests strongly that many of the deep passages may be the collapsed portals of underground streams.

Interpretation of atolls as subaerial erosion features modified by subsequent organic growth meets less objections than the theories that attribute atolls to growth alone. The presence of deep passages on some atolls and shallow or no passages on others has always been difficult to explain by growth alone. The development of such irregularities on a weathering limestone terrain requires no special explanation in view of existing solution forms. Subsequent organic growth might modify erosion features and growth forms might be influenced largely by food supplies and aeration. Corals would tend to fill in shallow passages more rapidly than deep passages owing to the lessser amount of light reaching the bottoms of the deep passages.

Effects of Solution on Emerged Atolls

The explanation for the origin of annular reefs just given assumes that atolls were once table or platform reefs, and that with emergence the platforms were weathered to saucer-shaped islands. An emerged atoll is by definition an atoll-shaped island that once was an atoll.

Emerged atolls can be assumed to already have an outer wall and a central depression when they emerge. Consequently, instead of having a single outer face, as a block would have, they have both an inner and an outer face. If the emerged reef is a broad flat, it might, on a smaller scale, weather like an emerged table reef.

Rims might develop along the edges of the raised reef and a minor depression or surface facet might develop along the flat (pl. 1-4). The central depression or lagoon would develop a system of subsurface drainage and, in time, a soil, both of which would promote solution and deepen the central depression.

The case of Kita Daito Jima.—Kita Daito Jima is a small island lying south of Japan and east of Okinawa between the Ryukyu and Marianas-Bonin arcs. The central part of the island is a suboval depression about a mile in diameter, in the bottom of which are two small lakes. The depression is surrounded by a limestone wall about 150 feet high and from half a mile to one and a quarter miles in width. On the western and southern sides of the island both the inner and outer margins of the wall have a well-developed rim (pl. 8). The top surface of the wall is slightly concave. The seaward slope of the island descends from the foot of the wall to the present sea cliffs in a series of terraces. Minor rims are developed locally along the edge of lower terraces.

If the interpretation of Kita Daito Jima as an emerged atoll (Saplis and Flint, 1949) is correct, the development of rims along both sides of the emerged reef flat might explain the origin of faros (pl. 1-5). Submergence of a double rimmed wall would provide a basement along which faros would develop, parallel ribbon reefs if it were continuous, and separate rounded faros if it were dissected. The well-developed series of terraces on Kita Daito Jima indicate that it was a pre-Pleistocene or early Pleistocene atoll that

emerged during Pleistocene time either by general eustatic lowering or by tectonic rising.

Faro-type atolls are common in the Maldive Islands and a few are known in the East Indies. None are known in the Marshall Islands. The prevalence of them in one region and the absence of them in another suggests that some regional phase relationship between ocean floor movement and glacial eustasy exists. If the series of terraces on the sides of Kita Daito Jima are proof of its Tertiary or early Pleistocene age, and we have thereby some measure of the time required to produce limestone walls, it may follow that the Marshalls lie in an area of continuous Pleistocene subsidence, whereas the Maldives, which lie on a continental shelf, either had an upward movement during Pleistocene time, or were abandoned temporarily by a general eustatic lowering, and have only recently been resubmerged.

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THE INFLUENCE OF CLIMATIC CHANGES ON THE FORMATION OF CORAL ISLANDS

HERMAN Th. VERSTAPPEN

ABSTRACT. In 1950 the author made a geomorphological study of the small reef patches lying in Djakarta Bay, an indentation of the Java Sea, with the object of investigating the influence of the wind on the development of coral islands. These islands, which have already been examined in great detail by others, made an excellent subject, as abundant meteorological data are also available. The islands that generally rest on these reef patches can easily be divided into three different parts, namely, the island proper built up of fine coral sand and therefore called the sand island, one or more shingle ramparts of coarse material, and, between these two, a shallow moat.

The position of the shingle ramparts with regard to their respective sand islands in 1950 is compared with former positions which can be inferred from old maps of the years 1875 (appr.), 1927, and 1939. A remarkable uniformity could always be established in the situation of the shingle ramparts on the various islands on maps of the same year, but the difference between the former and later positions appeared to be considerable. In 1875 the shingle ramparts were found especially on the northwest sides of the islands. In 1927, on the other hand, they were on the north, northeast, and east. In 1939 the formation of new shingle ramparts on the western sides had made fairly large progress; in 1950 these new western shingle ramparts had further developed.

The meteorological data show that during the years before 1927 strong east monsoons prevailed, whereas in the last few years of observation strong west monsoons occurred, as also in the years preceding 1875. These climatic changes are caused by the greater or lesser development of the Asiatic anticyclone area as expressed in the atmospheric pressure data of Hong Kong and by coincident shifts of the intertropical zone of convergence.

The coarse shingle ramparts always appear to originate on the weather side of the reefs and are afterwards gradually shifted in the direction of the islands by the surf. As appears from these investigations, the continually changing aspect of the shingle ramparts on the reef patches is brought about by climatic changes.

Many investigators have pointed out the influence exerted by the predominating wind direction on the orientation of alluvial shores, and also on the position of the beach ridges and the like. In the first standard work on coastal development by D. W. Johnson (1919) these points were treated at great length, while of the many later investigators especially the work of J. A. Steers (1948) in England and A. Schou (1952) in Denmark should be mentioned. In 1927 Umbgrove (1928, 1947) demonstrated the important part played by the wind in the development of coral islands, particularly with regard to the orientation of the islands in relation to the reef flats, and the distribution of coarse and fine material on those islands.

Umbgrove studied the coral islands occurring on about ten reef patches in Djakarta Bay. Besides the island proper that is built up of fine coral fragments or coral sand, he found also one or more shingle ramparts consisting of coarse coral debris and generally at some distance from the sand island, separated from the latter by a shallow moat. Fundamentally, the structure of these islands corresponds therefore with that of other reef islands elsewhere in the world. On all islands investigated by Umbgrove the coarse shingle ramparts appeared to develop by preference on the north, northeast, and east sides of the reefs, whereas the finer material that builds up the sand islands was everywhere found at the southwest side of the reefs. In connection with these facts he consulted the wind data of the meteorological observatory in Djakarta. In order to get a measure of the total "wind effect" in each of the

eight wind directions, he determined the product of the mean wind velocity (V) in each direction and the number of hours during which winds from that direction were observed (F).

It appeared to him that the total "wind effect," F x V, was greatest in winds from the north, northeast, and east, that is, on the sides where the shingle ramparts were found, whereas the product of F x V was smallest for southwest winds, that is, on the side where the sand islands are found. Umbgrove concluded, therefore, that the surf agitated by the wind caused the distribution of coarse and fine material and the position of the islands on the reefs as well, for finer material will be more easily shifted by the surf than coarser debris.

The influence of the wind on coral islands was thus convincingly shown, but a number of unsolved problems still remained. For instance, Umbgrove established that the distance between the shingle ramparts and sand islands, in other words, the width of the moats on the various reefs, differed considerably. At first he believed the width of the moats to be a criterion for the age of the islands. The older the islands the farther the shingle ramparts would have shifted toward the sand islands under the influence of the surf, and hence the narrower the moats would be. Later on, however, it appeared that the shingle ramparts shifted far more rapidly and that sometimes new shingle ramparts developed for no apparent reason. Hence their distance from the sand islands was quite independent of the age of the islands. An explanation of the changing picture exhibited by the shingle ramparts was not given, however.

For this reason, the author started a detailed investigation on the islands in Djakarta Bay in 1950. The results have been recorded in an extensive publication (1953). The present article contains the general conclusions drawn from this investigation of the causes underlying the changes of the coral islands.

During this study the following maps were at our disposal:

1. A topographical map to the scale of 1:20,000 of about the year 1875, showing little detail.

2. The map made by Umbgrove in 1927, with compass and pedometer, to a scale of 1:4000. This map is much more accurate than 1, and shingle ramparts, moat, and sand island are clearly noted.

3. The sketch map made of some of these islands by Hardenberg in 1939. It is less accurate than Umbgrove's map, but sufficient for the purpose. Scale 1:8000.

4. The map compiled by the author from transit survey during the 1950 investigations, to a scale of 1:4000.

Although these maps differ in accuracy, they succeed in giving a fairly complete picture of the development of the islands during the last 75 years. Figure 1 shows the island Njamuk besar (Leiden) as it appears on these four maps, to a scale of 1:8000.

In 1875 the island appears to have had a young shingle rampart (stippled in the figure) on the northwest and north side of the reef. Also the "peninsula" occurring on the northwest side of the sand island presumably was a shingle

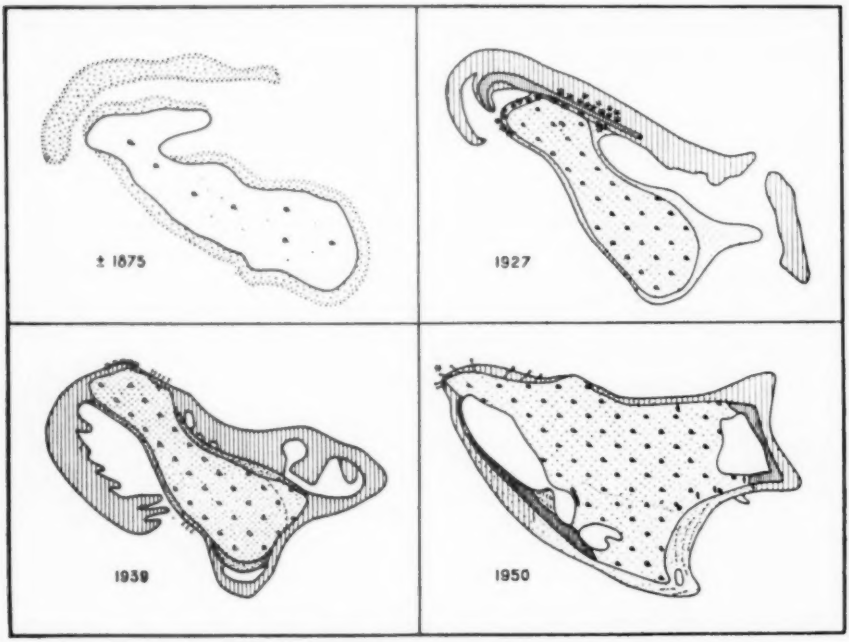

Fig. 1. The island Njamuk besar (Leiden) as it appeared in 1875, 1927, 1939, and 1950. Scale 1:8000. Key: stippled+trees: old nucleus; stippled: recent accretion (on the 1875 map also shingle ramparts); –.–.–: lines of growth; hatching: low shingle ramparts (or sparse shingle); dense hatching: high shingle ramparts.

rampart considering the moat developing east of it. In 1927 Umbgrove encountered a shingle rampart along the north, northeast, and east side, while at the northwest point a double curve of shingle ramparts was forming. The "peninsula" of 1875 had disappeared for the most part, and the shingle rampart rested against the sand island. Further eastward behind the shingle rampart there was a beautiful moat.

Hardenberg's sketch (1939) shows a later development. On the northwest point of the island the shingle rampart had disappeared, and abrasion of the coast had begun. Many fallen trees were found on the beach. The moat along the north coast had almost entirely filled except some parts lying most to the east. The overgrown part of the sand island had extended somewhat to the east. Remarkable were the changes along the west and northwest coast. The curving of the double shingle rampart observed by Umbgrove appeared to have lengthened along the entire west and southwest coast, so that a moat had originated on that side too.

In 1950 the moat no longer existed anywhere along the north coast, partly because it had been filled and partly because the abrasion had made so much progress that the coast was formed by the sand island that once lay inside the moat. Only on the east side could a last remnant of this moat still

be found. The whole north coast was subject to abrasion, especially the northwest point, as appears from the many uprooted trees. A last remnant of the "peninsula" of 1875, or of the area that connected the latter with the sand island, was formed by the somewhat projecting point on the north coast. The shingle rampart along the southwest side of the island extended

PLATE 1

A. The recent accretion at the lee (SE) side of Njamuk besar (Leiden) in 1951, looking toward the north. Note the lines of growth.

B. The moat at the southwest side of Njamuk besar (Leiden) in 1951, looking along it from its northwest end. The overflow in the shingle rampart by which the moat is in open connection with the sea at high tide is clearly shown on the right of the photo between the tree stump and the growth in the background.

even further than in 1939 and the moat lying behind had already partly filled. It had split in two parts, almost in three (pl. 1, fig. B). Fine coral sand was deposited near the little bay that had formed on the southeast side of the island. On this side the sand island had been extended. The surf caused some beautiful parallel ridges to develop in this material (pl. 1, fig. A).

Summarizing, it may be stated that in 1875 the shingle ramparts were found on the northwest and north side; in 1927, however, they occurred mainly on the north, northeast, and east side, though a new shingle rampart was already developing on the northwest point. In 1939 and especially in 1950 the shingle ramparts were found on the western side.

A study of the maps of the other islands in the bay of Djakarta yields a similar result. In broad outline the development of the shingle ramparts on all these islands has been identical and simultaneous. There is evidently a joint cause; only the small, nonfundamental differences can be accounted for by the different forms of the reefs.

As the wind causing the surf on the coasts of the island is known to be the agent of the distribution of coarse material (shingle ramparts) and fine material (sand island) on the reef flats, it was pertinent to trace how far changes have taken place in the local wind forces and the frequencies of wind directions in the course of years. To this end the available wind data of the observatory in Djakarta, which all refer to the period 1905-1944, were carefully analyzed. For all eight directions, the product of the number of hours

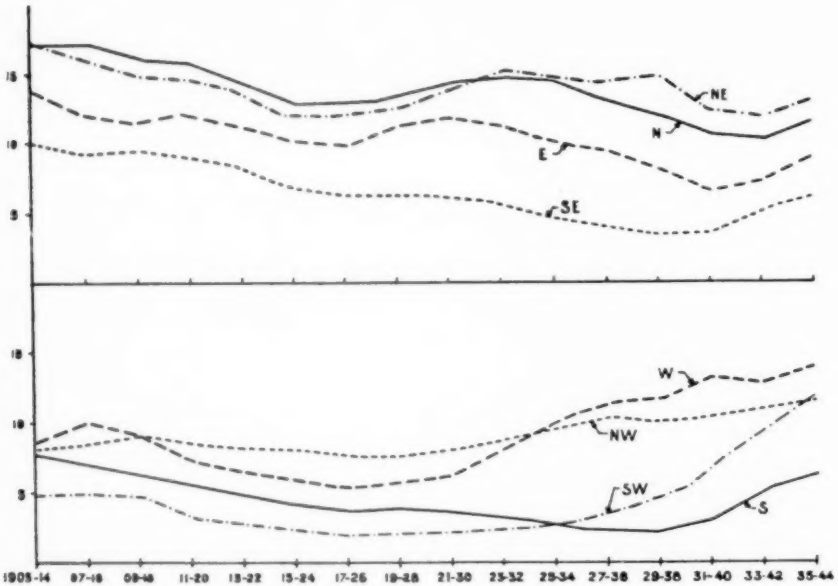

Fig. 2. The 10-year sums (moving averages) of the product of the frequency (F) of the wind in hours/year and the mean wind velocity (V) in m/sec. for the eight wind directions since 1905-1914.

during which the wind had blown from that direction, that is, the frequency (F), and of the average wind velocity (V) from that direction was calculated. In order to eliminate nonsignificant differences between the figures of the various years as much as possible and to extract only durable climatic changes, if any, 10-year sums (moving averages) were used. The results of these calculations are presented by the graphs of figure 2. It appears that the products, F x V, for all the wind directions are subject to considerable fluctuations. For instance, the product for the southwest winds during the period 1935-1944 was about six times the product for the period 1919-1928.

The most striking fact is the minimum for the south, southwest, and northwest winds in the second decade of this century and the maximum for the north, northeast, east, and southeast winds at the same time. Figure 3 shows the products, F x V, for the eight wind directions in 1917-1926, that is, for the ten years preceding Umbgrove's observations on the islands in the bay of Djakarta, and also for the last ten years for which wind data were available, namely, 1935-1944. This clearly shows the predominance of the north, northeast, and east winds during the first-mentioned period and the strong increase of the northwest, west, and southwest winds since that time.

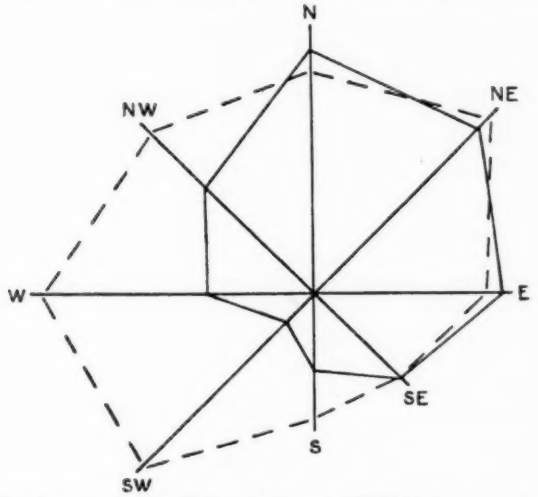

Fig. 3. Wind roses of F x V for the years 1917-1926 (————) and 1935-1944 (– – – –). The increase in the western directions is striking.

As Djakarta is situated in the Southeast Asia monsoon area, this indicates that the first-mentioned period was characterized by strongly developed east monsoons (dry monsoons) and the last-mentioned one by strong west (wet) monsoons.

Schmidt and Schmidt-ten Hoopen (1951) have also recently concluded that strong east monsoons prevailed about 1920-1930, on the basis of precipitation figures, dry- and wet-bulb temperatures, and sunshine data; since these meteorological elements have been observed over a longer period, they

arrived at the conclusion that strong west monsoons also prevailed at the beginning of this century. Moreover, from their precipitation figures heavy west monsoons about 1865 and after could be inferred, that is, in the period preceding the date of the oldest maps of the islands. Between these two older periods with strong west monsoons there must have been a period with more predominant east monsoons, presumably shortly before the turn of the century.

This alternating intensity of the monsoons is, as appears from the investigations of Schmidt and Schmidt-ten Hoopen, to be attributed to the greater or lesser development of the Asiatic anticyclone area during the winter months in the northern hemisphere. This is clearly illustrated by the data of pressure and precipitation for Hong Kong during the period of 1885-1939. A strongly developed anticyclone over Hong Kong is always attended with strong west monsoons over Java, while with less high atmospheric pressure over Hong Kong the east monsoons will prevail on Java. Further, the intertropical zone of convergence will, when the Asiatic anticyclone is strongly developed, be shifted as far as southern Indonesia. Since the highest precipitation figures and the strongest west monsoon winds occur along this front, a strong west monsoon is then reported in Djakarta. When, in consequence of a less high atmospheric pressure over Asia, the intertropical zone of convergence is situated over the north of Indonesia for a long period, east winds will predominate over Java.

Now that the existence of climatic changes in Indonesia has been sufficiently illustrated, and their cause has been pointed out, we have only to trace their general effect on the development of the coral islands as described on the preceding pages with the aid of maps. There appears to be a close relation between the two; in 1875 the shingle ramparts were found at the northwest sides of the islands and strong west monsoons prevailed. In 1927 shingle ramparts were met with along the north and east sector of the islands and the influence of the east monsoons was predominant. In 1939 the shingle ramparts were developing on the western sides of the islands, and also the west monsoons had increased in strength. In 1950 this increase appears to have continued.

Summing up, we can state that the shingle ramparts always form on the windward side of the reefs and that the recent accretion of the sand islands takes place mainly on the lee side. This is quite in accordance with Umbgrove's observations that the fine material is transported before it is deposited and that the coarse material is deposited at the weather side. *Every variation in the position of the shingle ramparts is evidently caused by climatic changes.* Even the direction of accretion of the new shingle rampart on the island Njamuk besar (Leiden) from the northwest via west and southwest to south is explained because, as the graphs show, the northwest winds first increased in strength and afterwards the west, southwest, and south winds successively increased likewise. If this had not been so, the shingle rampart would perhaps have originated everywhere simultaneously or would have grown in the reverse direction. Once a shingle rampart has developed it will gradually be shifted islandward by the surf. The moat will eventually

disappear. A fresh climatic change is then necessary to produce a new shingle rampart.

It would be interesting to complete these observations on the Southeast Asia monsoon area with an analogous investigation of the trade wind belt. Do climatic changes occur there also, and if so, what is the effect of these changes on the forms of the coral islands in those areas where the winds from one direction strongly predominate?

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LATE PRECAMBRIAN VOLCANISM IN SOUTHEASTERN ARIZONA

GORDON GASTIL

ABSTRACT. A hitherto unrecognized volcanic episode of late Precambrian age in southeastern Arizona is indicated by the discovery that certain rocks of the Pioneer formation, previously described as shale, are actually rhyolite tuff.

In a portion of southeastern Arizona the Paleozoic terrane is underlain disconformably by the Apache group of late Precambrian (?) age. As redefined by Darton in 1932, the Apache group consists of seven formations, in sequence: the Scanlan conglomerate lying unconformably on the older Precambrian basement rock, Pioneer shale, Barnes conglomerate, Dripping Springs quartzite, Mescal limestone, and basalt. In 1951, Peterson et al. substituted the name *Pioneer formation* for *Pioneer shale*.

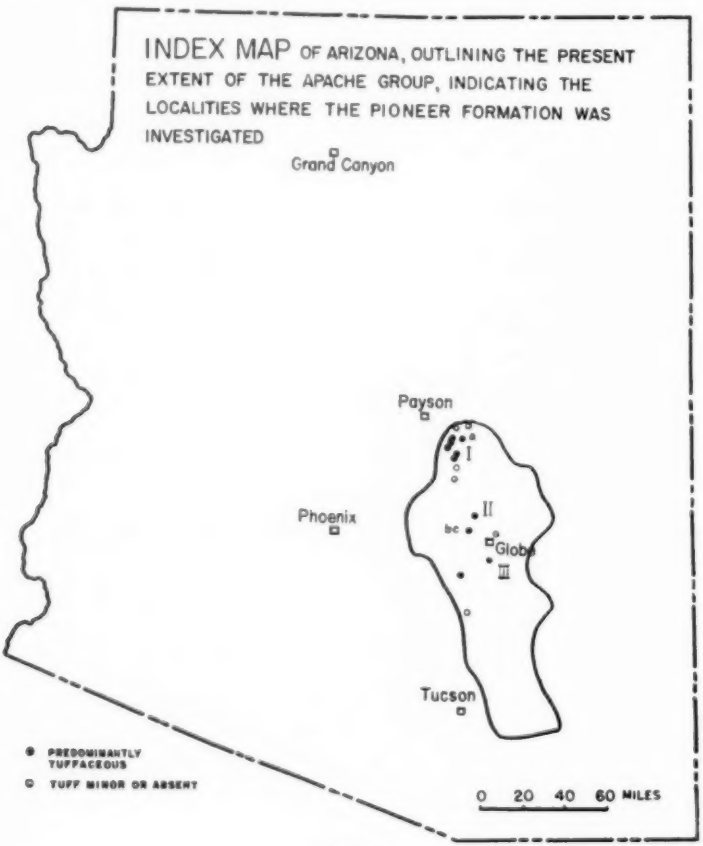

Fig. 1

The writer mapped the Pioneer formation in the Diamond Butte quadrangle, which is in the northern part of Gila County, and measured sections of it as far south as Pioneer Stage Station, in the Ray quadrangle, south of the Pinal Range. He also examined samples of the Pioneer formation collected by Mr. John White south of Superior, Arizona; and in the Tortilla Range, south of Ray. The Pioneer rocks studied consist of arkose grit and gravel conglomerate, feldspathic sandstone, argillaceous and feldspathic siltstone, silty mudstone, tuffaceous siltstone, and rhyolite tuff. Nine of the 12 measured sections consist entirely or predominantly of rhyolite tuff and tuffaceous siltstone. One section is composed principally of feldspathic sandstone, and two (both incomplete) consist of argillaceous siltstone and silty mudstone. The investigated localities are shown on the index map (fig. 1), three well-exposed, unbroken sections of the Pioneer formation are shown in figure 2, and photomicrographs of the tuff from two localities are shown in plates 1 and 2.

The rhyolite tuff and tuffaceous siltstone are characteristically pale grayish red in color (National Research Council, 1948). A large portion of the tuff is cross-laminated in beds a few inches thick, and typically, the tuff is finely bedded and brittle, the outcrops resembling shale, and forming receding slopes.

The shards of devitrified glass are composed of finely divided mica of the muscovite type, and very fine-grained chalcedony (determinations by X-ray powder pattern). Finely divided hematite gives the red color to the rock. The crystal fraction of the tuff consists of angular, silt-size grains of

PLATE 1

Photomicrograph (X200) of rhyolite tuff of the late Precambrian Pioneer formation of southern Arizona. Walnut Creek in the Diamond Butte quadrangle.

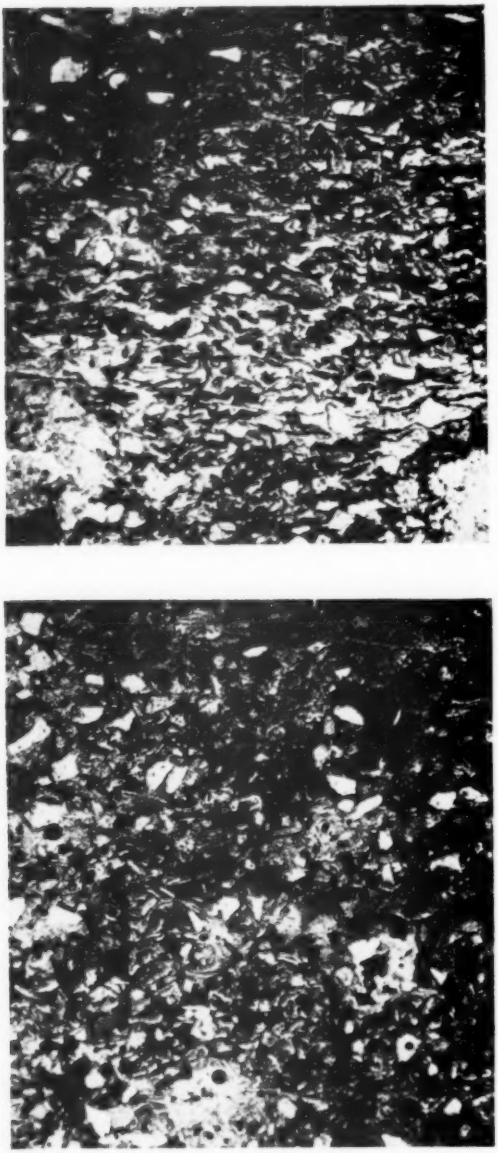

PLATE 2

Photomicrographs (X100) of rhyolite tuff of the late Precambrian Pioneer formation of southern Arizona. Gerald Wash in the Inspiration quadrangle.

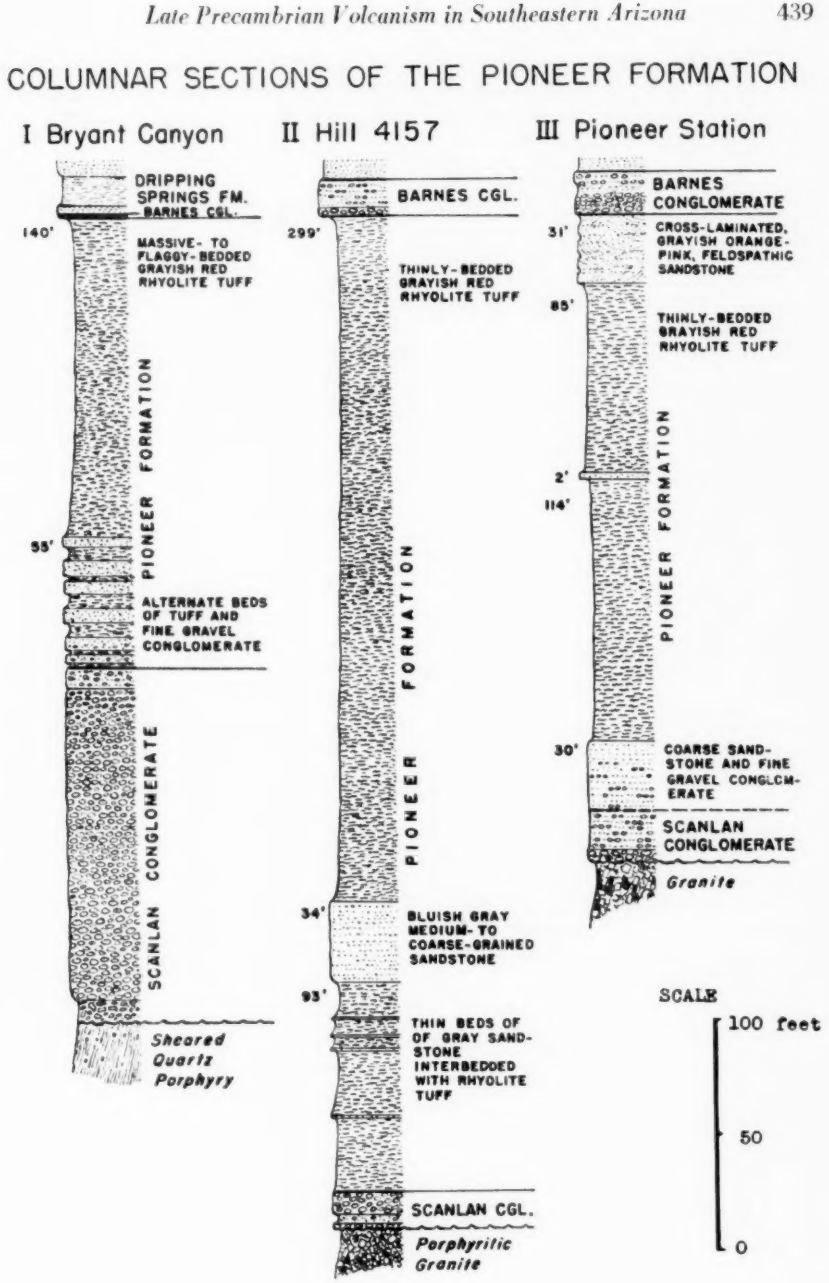
COLUMNAR SECTIONS OF THE PIONEER FORMATION
I Bryant Canyon
II Hill 4157
III Pioneer Station
DRIPPING SPRINGS FM.
BARNES CGL.
140'
MASSIVE- TO FLAGGY-BEDDED GRAYISH RED RHYOLITE TUFF
PIONEER FORMATION
55'
ALTERNATE BEDS OF TUFF AND FINE GRAVEL CONGLOMERATE
SCANLAN CONGLOMERATE
Sheared Quartz Porphyry
BARNES CGL.
299'
THINLY-BEDDED GRAYISH RED RHYOLITE TUFF
PIONEER FORMATION
34'
BLUISH GRAY MEDIUM- TO COARSE-GRAINED SANDSTONE
93'
THIN BEDS OF OF GRAY SANDSTONE INTERBEDDED WITH RHYOLITE TUFF
SCANLAN CGL.
Porphyritic Granite
BARNES CONGLOMERATE
31'
CROSS-LAMINATED, GRAYISH ORANGE-PINK, FELDSPATHIC SANDSTONE
85'
THINLY-BEDDED GRAYISH RED RHYOLITE TUFF
2'
114'
PIONEER FORMATION
30'
COARSE SANDSTONE AND FINE GRAVEL CONGLOMERATE
SCANLAN CONGLOMERATE
Granite
SCALE
100 feet
50
0

Fig. 2

quartz, albite, and muscovite. The proportion of crystal grains varies from near absence to predominance. In some tuffaceous siltstones, devitrified glass is mixed with grains derived from the basement rock.

Discovery of rhyolite tuff in the Pioneer formation indicates a hitherto unknown interval of volcanic activity during which a blanket of rhyolite ejecta and tuffaceous siltstone, perhaps averaging 200 feet in thickness, was deposited over an area at least 65 miles from north to south, and at least 20 miles from east to west (further investigation will probably extend the known distribution). Thin deposits of ash may have been deposited over an area with a radius measured in hundreds of miles, and careful search should be made for such beds in the late Precambrian formations of the Grand Canyon.

This study was made at the University of California, Berkeley, while the writer was a pre-doctoral fellow of the Oak Ridge Institute of Nuclear Studies.

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A STUDY OF THE OPTIC PROPERTIES AND PETROLOGIC SIGNIFICANCE OF ZONED SANIDINES

K. JINGHWA HSU

ABSTRACT. Zoned sanidine phenocrysts from a dacite intrusive of the southeastern San Gabriel Mountains, California, are composed of potassic cores (Or_{72}) and more sodic shells (Or_{60}). The cores have $2V_x = 15°$, z = b, $\beta = 1.526+$, $\gamma = 1.527+$, and $X \wedge a = 4°$; the shells have $2V_x = 30°$, z = b, $\beta = 1.528$, $\gamma = 1.529$, $X \wedge a = 8°$. The zoning suggests the trend of crystallization predicted by Bowen and Tuttle.

INTRODUCTION

Observed zoning in olivine, plagioclase, and other minerals can commonly be explained in terms of phase equilibrium studies and helps to interpret the course of crystallization of magmas. Zoned alkali feldspars have not been widely recognized, but they may add significant information for such interpretations. In the present paper the writer presents the results of investigations on the optical properties of zoned sanidine crystals and includes a brief discussion of the possibility of using such crystals to interpret the course of crystallization of sanidine-bearing rocks.

OCCURRENCE

The zoned sanidine studied is found in a dacite which occurs as a small hypabyssal intrusive near Voth Ranch (SW¼, sec. 7, T. 1 N., R. 7 W.) in Cucamonga Canyon area, southeastern San Gabriel Mountains, California (Hsu, 1953). The rock consists essentially of euhedral phenocrysts of oligoclase and quartz in a microcrystalline matrix of feldspars, biotite, and quartz. Only a few sanidine crystals are present, and these consist of a homogeneous core surrounded by a homogeneous shell.

OPTICAL PROPERTIES AND COMPOSITIONS

The optical properties of the alkali feldspars in the dacite indicate that they are members of the sanidine-anorthoclase cryptoperthite series of Tuttle (1952). Microscopic examination reveals that the cores of the zoned crystals have lower refraction indices, lower birefringence, and smaller axial angle than the shells, indicating that the cores are more potassic than the shells. The axial angles, as determined from acute bisectrix figures, are approximately 15 degrees about X in the cores and 30 degrees in the shells. Horizontal dispersion of the bisectrix figures indicates that the optic planes are perpendicular to (010).

The $KAlSi_3O_8$ contents of selected samples were determined by the X-ray method described by Bowen and Tuttle (1950, p. 491). The zoned crystals are only about 1 mm long, and therefore much too small to permit a clean separation of the shells from the cores. Consequently, whole crystals were pulverized to give a powdered mixture of two different compositions. In the X-ray diffraction records, two *distinct* "peaks" corresponding with 2θ values of 26.997 and 26.777 (for Fe$K\alpha$ radiation, calibrated against a quartz peak) are present. The reflection angles were then transformed into spacings of the (201) planes in the feldspars. The resulting d/n value for the more

potassic sanidine is 4.151, and that of the more sodic sanidine is 4.185. These values indicate that the former has a composition of Or_{77}, and the latter has a composition of Or_{60}. The two distinct peaks of X-ray reflection from (201) may represent a cryptoperthitic intergrowth of two feldspars or they may represent zoned crystals composed of sanidines of different compositions. The former alternative is practically nonexistent for the following reasons:

(1) Optical study shows that the sanidine crystals are definitely zoned and that they are apparently not perthitic.

(2) The positions of the (201) reflections of the sanidines remain unchanged on heating at 950°C. for two hours. This treatment is commonly sufficient to homogenize sanidines. Therefore, the sanidines are apparently not perthitic before heating.

(3) Alkali feldspars with compositions $Or_{77}Ab_{23}$ and $Or_{60}Ab_{40}$ could not have been formed from perthitic unmixing of a homogeneous feldspar, if the solvus curve for alkali feldspars established by Bowen and Tuttle (1950) is essentially correct.

Assuming the more potassic sanidine constitutes the cores of the zoned crystals and the more sodic sanidine constitutes the shells of the zoned crystals, the results of the X-ray studies agree with those of optical studies, which show that the composition of the core is approximately Or_{75} and that of the shell is approximately Or_{60}.

The optic orientations of the zoned sanidines were determined from universal stage studies. The results are summarized in table 1. The indices of refraction of the zoned crystals were determined on a thin section using the immersion method. The cover glass was removed from the thin section and scratch was made across the grain, into this were placed the immersion oils, thus making determination of the indices of the zones possible. Only the β and γ values were obtained, using a zoned grain with such an orientation that its Bx_a is perpendicular to the plane of the thin section. A sodium lamp was used, and the indices of the immersion oils were checked immediately after each measurement; thus the probable error of measurement is probably less than 0.001.

TABLE 1

Optic Properties of Zoned Sanidines

	Shell	Core
$2V_x$ (Determined by Bx_a figures)	30° ± 3°	15° ± 3°
$2V_x$ (Determined by extinction method)	25° ± 3°	14° ± 3°
Extinction angle on (010) against (001)	+ 8° ± 2°	+ 4° ± 2°
β	1.528	1.526+
γ	1.529	1.527+

Assuming that the compositions determined by the X-ray method are correct, the optic data of the zoned sanidine may be compared to those published by Tuttle (1952), to which they show good agreement. Future optical studies of alkali feldspars may improve Tuttle's curves to such an extent that it will become possible to use the petrographic microscope to determine the $KAlSi_3O_8$ content of alkali feldspars.

PETROLOGIC SIGNIFICANCE

The trend of crystallization suggested by the alkali feldspars described above is in agreement with experimental results. Bowen and Tuttle (1950), in studying the system $NaAlSi_3O_8$—$KAlSi_3O_8$—H_2O, found that alkali feldspars form a complete series of solid solutions of the type having a minimum melting member. For melts with composition more potassic than $Or_{35}Ab_{65}$, potassic sanidine is the first feldspar to crystallize. On further cooling, the sanidine becomes richer in Ab component. Thus, more sodic sanidine shells around potassic cores should be formed if equilibrium is not attained. The zoned sanidines in the dacite of the Cucamonga Canyon area illustrate a crystallization process very similar to that outlined above.

ACKNOWLEDGMENTS

The writer is indebted to Dr. O. F. Tuttle for his advice, and to W. Lawrence Knight and Frank W. Dickson for their assistance in analyzing the sanidine specimens. He has benefited through discussions with M. F. Carman and T. H. McCulloh.

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REVIEWS

Spezielle Mineralogie auf geochemischer Grundlage; by FELIX MACHATSCHKI. P. 378; 288 figs. Vienna, 1953 (Springer-Verlag, $8.60).—Dr. Machatschki has adopted for his presentation of minerals a petrogenetic ("geochemical") arrangement. Minerals of orthomagmatic origin and their structural relatives (e.g., micas, including lepidolite) are followed by epimagmatic minerals (pegmatitic-pneumatolytic series; hydrothermal gangue minerals; volcanic minerals), then by minerals resulting from weathering and sedimentary processes, then metamorphic minerals. The ore minerals are placed in a separate section. A 53-page appendix contains a "Crystal-chemical system of minerals." The divisions may be outlined as follows:

GROUPS, based on presence or absence of neutral molecular groups such as H_2O.

ORDERS, based on the number of crystallographically different chemical elements.

CLASSES, based on specific chemical formula-type, as $ABCDE_4$.

FAMILIES, based on crystal symmetry and coordination of atoms, as

$$\infty^2 A^{[12]}\{B_{2\text{-}3}^{[4+2]}C_2[D_4^{[4]}E_{10}]\}m;\ C_{2h}^{6} - C2/c$$ for the micas.

Formulas throughout the book are given in this form. The significances of unusual symbols are as follows: ∞^2, two-dimensional sheet structure; $^{[n]}$, coordination of anions about a cation; m, monoclinic; space group in Schoenflies and international symbols.

SPECIES, (isomorphous series), as Muscovite, including paragonite, phengite, oellacherite, fuchsite, roscoelite, and lepidolite.

This classification has much to recommend it; one cannot object to the juxtaposition of galena, periclase, and halite but would be pleased to find nearby all other minerals with related structures, including, for example, schapbachite (= matildite, $AgBiS_2$) which has an ordered galena-like structure. High-temperature schapbachite has a disordered galena structure (Ag,Bi)S, and must be classed with galena under Machatschki's system. Thus an order-disorder transformation may separate high- and low-temperature forms of the same compound rather widely. It is almost always easy to find minor flaws and to compare examples of the worst of a new system with the best of a familiar old one. Dana chose to classify minerals first by the dominant anion; Strunz stayed with that principle. Machatschki has chosen instead a truly crystal-structural basis for his major emphasis. Both systems have important merits.

The book as received contains a short list of errata. A few more were found by the reviewer, such as the incorrect statement of optic orientation in biotite on page 51 [$n\alpha$, not $n\gamma$, is $\perp$ (001)], or some obvious errors in symmetry symbols [e.g., F43m, not F43m on p. 305, l. 5] and in a few

bring the whole treatment more nearly in accord with the most recent international usage. Footnotes throughout the book clearly distinguish most of the changes thus made. The reference to p. 17 in the legend to plate V A, and chemical formulas [e.g., berzelianite and yttrofluorite, p. 306]; an incorrect page reference is given in the list of errata itself [S. 329 for S. 328].

No review would be complete without a word of appreciation for the well-selected classified bibliography (p. 354-355) and the excellent index of more than 2500 items (many with several page references).

This book signals the beginning of a new kind of thinking by mineralogists. We hope it will be continued, and we are confident of its success under the hand of its competent and distinguished author.

HORACE WINCHELL

Crystal Structures, Section III and Supplement II; by RALPH W. G. WYCKOFF. P. 700. New York, 1953 (Interscience Publishers, Inc., *Section III* $14.50, *Supplement II* $4.00).—For the inconvenient pagination of Wyckoff's *Crystal Structures* we are fully compensated by the regular supplements that are now appearing from time to time. For the work as a whole there is no substitute. Section III here under review contains a supplement to chapter XIII (Structures of aliphatic compounds), and two new chapters: XIV (Structures of benzene derivatives) and XV (Alicyclic and heterocyclic compounds, and carbohydrates).

There now remain only chapters XI-XII (hydrates and silicates) and a general index still in preparation. The reviewer has found the portions of this work so far available to be arranged well enough to allow fairly ready reference; the index still to come will no doubt facilitate finding compounds by mineral name or other non-chemical name. In spite of its lamentable price, this indispensable work will find constant use by all research groups interested in crystal structure.

HORACE WINCHELL

X-ray Crystallographic Technology; by ANDRE GUINIER. English edition, 1952, translated by T. L. Tippell from the Paris edition of 1945. P. xiii, 330; 145 figs., 16 pls. London (Hilger and Watts, Ltd.; Jarrell-Ash Co., Newtonville, Mass., $9.50).—Twelve chapters are grouped into five Parts, the subjects of which are as follows: Part I, X-rays; II, Crystallography and diffraction theory; III, Experimental methods; IV and V, Applications, Part V including studies of crystal imperfections, amorphous materials, and particle sizes. No material is included on actual solutions of crystal structures. Appendices I to X (p. 271-322) outline the essential mathematical and physical details of projections, of summation of waves, of scattering of X-rays by an electron, by an atom, by a crystal, by a powder, and by an amorphous substance; and they include useful physical and mathematical tables.

"This book is addressed specially to technicians who want to use the methods of X-ray crystallography, and not to crystallographers" (p. ix). Dr. Kathleen Lonsdale, in her foreword to this translation, notes the adoption of

Angstroms in place of kX units, and a few other translator's changes that a transposition of titles in the legend of figure 27 are in error; these and others that I have found are relatively obvious, and therefore unimportant.

This book will be useful in the many laboratories that are not concerned with the ultimate solution of crystal structures *per se*.

HORACE WINCHELL

Pétrographie des Roches Sédimentaires; by ALBERT CAROZZI. P. 258; 27 figs. Lausanne, 1953 (F. Rouge & Cie. S.A., Librairie de l'Université, 23.40 Swiss francs).—Carozzi's textbook is based upon a course given in the University of Geneva since 1948. The book is not intended as a monograph on the subject but is an up-to-date introduction and summary. Petrography of the consolidated sedimentary rocks is emphasized, but sufficient material pertaining to the geologic processes involved in the formation of sedimentary rocks is included to round out the text. A working knowledge of the fundamentals of microscopic examination is presupposed by the author, who does not pause to describe special features shown by the various varieties of minerals commonly encountered in thin-section examination of sedimentary rocks or to define the textural terms employed. References to both European and American literature are listed at the end of the chapters concerned only, with some inevitable repetition of titles. Many references to current European work commonly unnoticed in this country will be found here. The book lacks an index, but the table of contents is fairly comprehensive.

The three parts into which the book is divided differ considerably in size. A brief discussion of the commoner detrital minerals comprising the first part (31 pages) emphasizes the varieties of quartz and feldspar. Considering the scope of the book and the amount of information concerning provenance that must be derived from a study of detrital fragments in petrographic work, this section is treated cursorily and with few illustrations.

Three chapters (62 pages) are devoted to the usual threefold division of detrital rocks, but employing the boundaries of Cayeux, at 5 and 0.05 mm. Coarse-grained and fine-grained rocks are subdivided according to method of origin, and the more common varieties are included, with the exception of lag concentrates. Classification of the medium-grained rocks is based chiefly on the cement, but some categories are erected to include the presence of unusual components among the fragments. Of special interest to American workers are the descriptions of "molasses," "macignos," and graywackes; Carozzi defines graywacke as a sandstone containing a minimum of 33 percent of minerals easily destroyed in weathering and/or rock debris of basic rocks, phyllites, and dark schists, rather than as the "ferro-magnesian equivalent of arkose." Graded bedding is not considered to be an inseparable component of the definition of graywacke. Carozzi treats all fine-grained rocks under the heading of "*argilites*," though he seems to invite confusion by accepting Flawn's recently proposed terminology for the faintly metamorphosed argillaceous rocks in which the term "*argillite*" is employed for such a rock in which less than half the clay minerals have been reconstituted into metamorphic minerals. A useful table comparing German, English, and French termi-

nology for the argillo-calcareous rocks is given on page 88. The chapter on fine-grained rocks summarizes much of the recent research on the clay minerals and leans heavily upon the work of Urbain and Millot; the implications of Millot's data on the variation of clay minerals with conditions of deposition appear very striking.

The third and largest division of the book (152 pages) concerns biochemical rocks (including strictly chemical rocks). The large amount of space devoted to ferruginous rocks, phosphatic rocks, salines, and coals in this section stands in contrast to the small emphasis commonly given these topics in American courses of sedimentary petrography. Especially valuable here are the treatment of oölite, non-detrital siliceous rocks, and oölitic iron ores, subjects of Carozzi's previous publications. The last, particularly, seems to the reviewer to form a model on which other portions of the book might profitably have been elaborated; concrete examples buttress the discussion, whereas other sections consist largely of abstract descriptions, with mere mention of a few examples.

In the opinion of the reviewer, the book could be improved greatly by the inclusion of more illustrations and discussions of actual examples. As it stands, however, the book will be valuable to Americans for its illuminating descriptions of many rock types generally unfamiliar here, for its bibliographies, and for its different emphasis.

JOHN E. SANDERS

An Introduction to the Theory of Seismology, 2d ed.; by K. E. Bullen. P. xv, 296; 43 figs. New York, 1953 (Cambridge University Press, $6.50).—The revised edition of Dr. Bullen's text on Seismology contains few changes from the 1947 edition. The main addition is a list of classified references which present the reader with other authors he might consult, they being the sources of a great deal of the author's material.

The fact that little has been revised in this new edition does not detract from the book. As one knows who has taught from this text, it is an excellent book, perhaps one of the best to teach the fundamental theory of elasticity, wave motion, strain, etc., and is a book that should be on the shelves of every library on seismology or geophysics. The book should not be attempted by most students alone, but with the guidance of the teacher. Once a student has been introduced to the science and has become better experienced with the concepts of geophysics, then it will also make an excellent reference for him.

The author does not intend to give a text that will serve as a directive in operating a station or an observatory. He helps but little in teaching one how to interpret records, although he does go into the nomenclature of phases at extra length. While the theory of seismic instruments is well explained and proven, there is insufficient explanation on individual instruments and the reason why one type should be chosen before another.

Another very good section is the author's exposition of the stripped earth and the delineation of the various shells that make up our earth. Other

texts may spend more time on this problem, but Dr. Bullen has treated the major points very well and, as is usual with him, very clearly.

His striving for brevity has gone a little too far, at least in the mind of this critic, in the chapter on "Further Topics." Such items as The Effects of Earthquakes, Microseisms, Building Construction, Seismic Prospecting, etc., should have been explained more extensively. This would not have detracted from the main purpose of the text. As long as they were mentioned at all, they should have been a bit better developed. These show the more practical application of the theory he has been developing.

The list of classified references is very good, and the author has picked from the cream of the more recent and current writers. There are some texts that the critic would have added to make the list more complete.

J. F. DEVANE, S. J.

The Metabolism of Algae; by G. E. Fogg. P. 149. Methuen's Monographs on Biological Subjects. London and New York, 1953 (Methuen & Co., Ltd., and John Wiley & Sons, Inc., $2.00).—Dr. Fogg has written a short book, one that can easily be read in about one hour, but he has succeeded in presenting in these few pages a critical survey of all the essential features of algal physiology. The difficulties of such a presentation are twofold: first, any book on a biochemical topic threatens to become obsolete while being written; second, little biochemical work has been done on the algae as compared to the bacteria, fungi, and higher animals. The author had therefore the task of producing an up-to-date account of those physiological features which algae have in common with other living beings (but which have largely been investigated in organisms other than algae), while emphasizing the metabolic peculiarities of the algae. This task the author has carried out in a distinguished manner. He discusses algal metabolism largely from the nutritional point of view, devoting about two thirds of the book to autotrophic and heterotrophic assimilation and its biochemical basis. The remainder of the book deals with the main metabolic products in algae and with their growth.

The emphasis on the chemical basis of algal metabolism should serve to call to the attention of biochemists the specialized problems which the algae present, and should also interest them in using algae as subjects for general studies. The emphasis on algal chemistry is given a sound biological basis in brief discussions of the systematics and natural history of the algae. The author refers to the polyphyletic origin of the algae and points out the term "alga" is a convenient collective term for organisms that have certain physiological characters in common, much as "yeast" is a collective term in microbiology. The table showing the taxonomic affinities of all genera mentioned in the text should be particularly welcomed by readers new to phycology. Such amenities are too frequently omitted.

The book is attractively printed and bound, and is a convenient and valuable review for plant physiologists and microbiologists.

WOLF VISHNIAC

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